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NCRP REPORT No. 65

MANAGEMENT OF PERSONS ACCIDENTALLY CONTAMINATED WITH RADIONUCLIDES

NCRP

National Council on Radiation Protection and Measurements

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of this and other NCRP Reports see page 199]

NCRP REPORT No. 65

MANAGEMENT OF PERSONS ACCIDENTALLY CONTAMINATED WITH RADIONUCLIDES

Recommendations of the
NATIONAL COUNCIL ON RADIATION PROTECTION
AND MEASUREMENTS

Issued April 15, 1980

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Preface

With the increased use of radionuclides in all fields of science and technology, the NCRP determined to review the scientific literature and select that body of information which represents the state of the art in the management of contaminated individuals. A committee was selected that was composed of those individuals who could bring the necessary expertise and experience together to write a manual that would be useful to the physician in the management of accidents involving radionuclides. It was recognized that the subject is not a normal requirement of a medical student's curriculum and that, only by attendance at training courses specifically aimed at the subject of managing radiation accidents, would a physician gain any insight into the problems involved in the treatment of casualties, where the presence of the contaminant was detectable only by use of special equipment.

It is a tribute to the safety record of the industry that there is not a vast amount of experience to draw on. There are scattered incidents that have been reported in the world's literature.

This manual is intended to assist individuals faced with the problem of managing an accident involving radioactive contamination to make the decisions necessary in selecting the treatment techniques that have been successful in the past or, in the case of a situation where there is no experience, the treatment techniques that appear to be the most rational.

The NCRP wishes to emphasize the fact that this report is intended only as an aid and guide for those called on to manage an accident case in its initial stages and cannot be used as a substitute for the knowledge and judgment of the responsible physician or for the information and advice available from those specialists who have had actual experience with such cases and who have pondered all of the potential difficulties that arise in such cases. Responsibility for the management of such cases must, of course, rest with the physician in charge.

The Council has noted the adoption by the 15th General Conference of Weights and Measures of special names for some units of the Systeme d'Unites International (SI) used in the field of ionizing

radiation. The gray (symbol Gy) has been adopted as the special name for the SI Unit, of *absorbed dose*, *absorbed dose index*, *kerma*, and *specific energy imparted*. The becquerel (symbol Bq) has been adopted as the special name for the SI unit of *activity* (of a radionuclide). One gray equals one joule per kilogram and one becquerel is equal to one second to the power of minus one. Since the transition from the special units currently employed—rad and curie—to the new special names is expected to take some time, the Council has determined to continue, for the time being, the use of rad and curie. To convert from one set of units to the other, the following relationships pertain:

$$1 \text{ rad} = 0.01 \text{ J kg}^{-1} = 0.01 \text{ Gy}$$
$$1 \text{ curie} = 3.7 \times 10^{10} \text{ s}^{-1} = 3.7 \times 10^{10} \text{ Bq (exactly)}$$

Serving on the Committee for the preparation of this report were:

George L. Voelz, *Chairman*
Health Division Leader
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

H. David Bruner
Route 1, Box 3397
Bonita Springs, Florida

Thomas A. Lincoln
Medical Director
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Victor H. Smith
Biology Department
Battelle Pacific Northwest Laboratories
Richland, Washington

Herta Spencer
Chief, Metabolic Section
Veterans Administration
Edward Hines, Jr. Hospital
Hines, Illinois

Niel Wald
Chairman, Department of Industrial Environmental Health Sciences
Graduate School of Public Health
University of Pittsburgh
Pittsburgh, Pennsylvania

Consultant
John W. Healy
Health Division
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

NCRP Secretariat, James A. Spahn, Jr.

The Council wishes to express its appreciation to the members and the consultant of the Committee for the time and effort devoted to the preparation of this report.

WARREN K. SINCLAIR
President, NCRP

Bethesda, Maryland
October 15, 1979

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1. Introduction

Increasing use of radionuclides in research, medical applications, nuclear power, and industrial processes suggests that there is also a concomitant increase in the probability of human exposures to internally-deposited radionuclides. It is important that such exposures be minimized, especially by preventive means, but good medical management is important when exposure has occurred. The literature on medical management of such cases is scattered and sparse. Any individual physician or health physicist probably will have had experience with only a limited number of radionuclides and a limited variety of exposure conditions. Furthermore, the therapeutic effectiveness of some treatments has been tested only in animals. Other therapies may be thought to be useful but have not been evaluated for a particular radionuclide or accident situation. This report is a collection of many of these data and ideas into one document to aid those called upon to manage contaminated persons.

Persons who use this report will probably represent a broad spectrum of professional personnel, but the NCRP has directed its attention and recommendations primarily toward the physician who assumes responsibility for a case. He may be an occupational physician, emergency room physician, military physician, general practitioner, nuclear medicine specialist, physician consultant to the nuclear industries, or a public health physician. Hospital staffs should find this report of sufficient value to make it available in their emergency rooms. Nurses, ambulance attendants, rescue squads, and other paramedical personnel will find sections relating to their duties. Health physicists will find useful information that will contribute to their role in the management of accident cases.

It is recognized that many aspects of medical management depend on judgment and evaluation that are difficult to express in words. Some portions of the report present collective opinions that are intended to assist in such judgment and evaluation, but it must be recognized that there is considerable latitude in the professional judgment of physicians as to the extent and intensity of treatment of a particular case. This report will be a guide and aid in the general management of such cases, but it is not intended as a model or standard for medical practice.

Several problems exist concerning the use of some medications that are effective in the treatment of persons internally contaminated with radionuclides. Experimental studies have shown some materials to be useful, but they have not been considered for approval as a drug by the Food and Drug Administration, or they are available only as an Investigational New Drug under approved study conditions. Information demonstrating the experimental effectiveness of such compounds in reducing exposures to internal radionuclides is summarized along with the available information on toxicity of such compounds.

The report is written so that useful advice can be rapidly obtained by consulting the "Quick Reference Section," pages 3 to 19. The first four tables in this section are check lists that will guide the gathering of information so as to focus the early efforts to deal with the particular problem. Table 2.5 is a summary of treatment considerations for selected radionuclides and an index to the appropriate sections of the report. Table 2.6 provides information on selected radionuclides that can be used in preliminary assessment of the consequences of an exposure. More definitive dose estimates must be made using the specific details of the exposure, including the chemical and physical form of the nuclides involved, and the latest data on these radionuclides.

It is important to emphasize that management of these cases requires a team effort by many specialists. The evaluation and management of such accident cases should utilize the help of professional health physicists, analytical chemists, and dosimetry (internal and external) specialists, as well as medical specialists.

This NCRP report is intended as an aid and guide for those called to manage an accident case in its initial stages and cannot possibly substitute for the information, advice, and judgment available from the above specialists.

2. Quick Reference Information

TABLE 2.1—*On-site emergency check list*

Note: The sequence and priority of these actions will vary with different accident conditions.

- Provide emergency medical care immediately for serious injuries and preserve vital functions. Minor injuries can wait until after initial radiation survey has been completed.
- Remove individual from contaminated radiation area. Individual doses up to 100 rems may be permitted for life saving purposes or up to 25 rems for less urgent needs (NCRP, 1971). Teams may be used in relays to remove injured persons from very high radiation areas.
- Survey individual for surface contamination levels.
- Get nasal smears. Do this before showering (Sections 3.4.1 and 4.1.4).
- Remove contaminated clothes and replace with clean coveralls or wrap in blanket. Take individual to an area where skin decontamination or showering can be done.
- Decontaminate skin. Remove all transferable contamination if possible (Sections 3.7.4 and 7.1.5) by cleansing contaminated skin areas and showering.
- Cover contaminated wounds with sterile dressings before and after decontamination efforts (Section 7.2.5).
- Alert hospital and call for ambulance service as soon as it is determined that it is needed. Apprise them of situation if their help is required (Section 3.5.7).
- Identify radionuclide(s) involved in the accident and, if possible, ascertain its chemical form, solubility, and presumed particle size.
- Send personnel radiation dosimeters for processing.
- Get complete history of accident (Section 3.8.1), especially as it relates to the activities of the individual. Where was he? What was he doing? Exit path? Symptoms?
- Evaluate possibility of penetrating radiation exposure (Section 3.5.6).
- Advise individual on collection of all excreta (Section 3.5.8). Provide containers. Save other contaminated materials (Section 3.5.9).
- Be sure someone has assumed responsibility for management of the accident area. Is radiological assistance needed? Who will request it? From whom?
- Report your initial responses and evaluation to the plant manager (Section 3.5.4).
- Get names of supervisory and health physics personnel who will remain on call in case additional information is needed (Section 3.5.7).
- Take individual to the hospital if injuries require surgical care not available at plant or if further medical or dosimetric evaluation and treatment is required.
- Take precautions to prevent spread of contamination during transport and movement of the patient (Section 3.6). Have transport vehicles, attendants, and equipment checked for residual radioactive contamination before release from hospital area.
- If environmental contamination outside the plant has occurred, notify public health authorities (Section 3.9).
- Advise family and next of kin on the extent of injuries and exposure (Section 3.5.4). Plant management personnel and the medical department personnel should agree on the proper procedure.
- Find out where to send bioassay specimens and length of time required for analysis. Specify who will receive the results.

TABLE 2.2—*Identification tag information*

Note: Each patient should be identified with as much of the following accident and treatment information as is available before sending to decontamination center or hospital. Health physicist or company physician should keep in contact with the hospital to supply additional information as needed.

a. Name of patient, employer, company number.
b. Physical injuries and treatment.
c. Skin surface contamination: its location, dose rate and/or count rate measurements initially and after decontamination, and description of decontamination methods and agents used.
d. Internal contamination.
   (1) Radionuclide, its chemical form, probable solubility, and possible particle character.
   (2) Suspected route of contamination.
   (3) Nasal counts.
   (4) Wound counts.
   (5) Whole body counts.
   (6) Bioassay samples already collected.
   (7) Treatment initiated.
e. External exposure to penetrating radiation.
   (1) Precise location and position of the patient relative to the source of radiation at time of exposure.
   (2) Exact time and duration of exposure.
   (3) Was dosimeter being worn? Where? What types?
   (4) Has dosimeter been collected? By whom? Where is it now located?
   (5) Symptoms; type and time of occurrence.
   (6) Describe other dosimetric studies underway.
   (7) Treatment.
f. Name and phone number of company health physicist or physician for additional information.

TABLE 2.3—*Medical information check list*

Note: These questions can be used by the attending physician at the hospital for obtaining historical information to assist in the early management of radioactively contaminated persons. The best information in industrial cases can probably be obtained from plant personnel, such as the health physicist or occupational physician familiar with the plant and accident details.

- When did the accident occur? What are the circumstances of the accident and what are the most likely pathways for exposure? How much radioactive material is involved potentially?
- What injuries have occurred? What potential medical problems may be present besides the radionuclide contamination?
- Are toxic or corrosive chemicals involved in addition to the radionuclides? Have any treatments been given for these?
- What radionuclides now contaminate the patient? Where? What are the radiation measurements at the surface?
- What information is available about the chemistry of the compounds containing the radionuclides? Soluble or insoluble? Any information about probable particle size?
- What radioactivity measurements have been made at the site of the accident, e.g., air monitors, smears, fixed radiation monitors, nasal smear counts, and skin contamination levels?
- What decontamination efforts, if any, have already been attempted? What success?
- Have any therapeutic measures, such as blocking agents or isotopic dilution been given?
- Was the victim also exposed to penetrating radiation? If so, what has been learned from processing personal dosimeters, e.g., film badge, TLD, or pocket ionization chamber? If not yet known, when is the information expected?
- Has clothing removed at the site of accident been saved in case the contamination still present on it is needed for radiation energy spectrum analysis and particle size studies?
- What excreta have been collected? Who has the samples? What analyses are planned? When will they be done?

TABLE 2.4—*Hospital decontamination procedures for protection of personnel and facilities*

- Personnel should wear surgical scrub suits, surgical caps and gowns, and rubber gloves (surgical, household, or industrial depending upon duties).
- The team leader should be trained to recognize the rare instance when there may be a need for masks, respirators, or supplied airpacks due to the presence of high levels of alpha or beta radionuclides.
- Rubber or plastic shoe covers are desirable. Those performing the actual decontamination with water should wear plastic or rubber laboratory aprons. Good temporary shoe covers for dry areas can be improvised from brown paper bags held on with adhesive or masking tape.
- Air conditioning and forced air heating systems should be turned off so radioactive particulates are not carried into ducts or to other rooms unless a special filter system has been designed for use under these conditions.
- The floors should be protected with a disposable covering to reduce "tracking" by keeping cleaner surfaces and to aid the clean up tasks. The covering should be changed when significant contamination is present. Brown paper rolls (36 inches wide, 60-pound weight) are ideal where water is not used. Plastic sheets are useful where spillage of liquids is a problem, although ribbed or non-skid types should be used to reduce the chance of slips and falls.
- All contaminated clothing should be placed carefully into plastic or paper bags to reduce secondary contamination of area.
- Splashing of solutions used in decontamination should be avoided.
- Patients and other potentially contaminated personnel may move to clean areas only after surveys show satisfactory decontamination.
- All passage of persons and property between contaminated and clean areas must be surveyed and regulated by monitoring teams.
- Supplies are passed through monitoring stations from clean areas to contaminated areas. Reverse flow must not occur unless supplies are monitored and found clean.
- All individuals on the decontamination team shall be trained in radiological monitoring and decontamination techniques. Persons not working on the team should be excluded from the work area.
- Fiberboard or steel drums with tight fitting tops should be obtained for contaminated materials. Labels describing the contents should be affixed so that proper disposal can be carried out without reopening them. They may be sealed with masking tape or some other type of sealing tape.
- Personal dosimeters (pocket chambers, film badge or TLD dosimeters) should be supplied to all personnel working in the decontamination area. Personnel should be rotated after a dose of 5 rems (or less if possible) is received.
- The entry of all non-essential personnel including family, visitors, and administrative persons should be restricted.

TABLE 2.5—*Treatment summary for selected elements*

The benefit from therapy recommendations in the Immediate Actions (Col. 2) and Drugs to Consider (Col. 3) columns will be influenced by the route of exposure—ingestion, inhalation, skin absorption, injection, or contaminated wounds. The chemical form and solubility of the radionuclide will also change markedly the efficacy of the recommended treatment. This table lists therapeutic procedures or drug therapy that may be helpful for the listed element in the favorable circumstances. The user is advised to consult the text for details on the influence of these other factors. The numbers in this table refer to sections in the text where additional information is available.

Element	Immediate actions	Drugs to consider	Information and comment
Americium (Am)	7.3.5.3–DTPA	7.3.5.3–DTPA	See Section 6.1.
			See Section 7.2 for contaminated wounds. Chelation should be started as soon as treatment decision can be made. CaEDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available.
Arsenic (As)	Consider 7.3.2.2–Lavage	7.3.5.4–Dimercaprol	Short-lived isotopes. Use of dimercaprol (7.3.5.4) is not indicated except in massive exposures.
Barium (Ba)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	See comment.	Use of sodium or magnesium sulfate with and after stomach lavage will precipitate insoluble barium sulfate.
Calcium (Ca)	Consider 7.3.2.2–Lavage, 7.3.2.4–Purgatives, and 7.3.3.6–Calcium	7.3.3.6–Calcium 7.3.4.4–Furosemide	Massive exposure may warrant use of the *sodium* salt of EDTA (7.3.5.2), but with caution over a 3–4 hour period to avoid tetany. Furosemide (7.3.4.4) enhances urinary excretion.
Californium (Cf)	7.3.5.3–DTPA, Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.5.3–DTPA	See Section 6.2. See Section 7.2 for contaminated wounds. Chelation should start as soon as treatment decision is made. Ca-EDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available.

TABLE 2.5—*Continued*

The benefit from therapy recommendations in the Immediate Actions (Col. 2) and Drugs to Consider (Col. 3) columns will be influenced by the route of exposure—ingestion, inhalation, skin absorption, injection, or contaminated wounds. The chemical form and solubility of the radionuclide will also change markedly the efficacy of the recommended treatment. This table lists therapeutic procedures or drug therapy that may be helpful for the listed element in the favorable circumstances. The user is advised to consult the text for details on the influence of these other factors. The numbers in this table refer to sections in the text where additional information is available.

Element	Immediate actions[a]	Drugs to consider[a]	Information and comment
Carbon (C)		No treatment available.	Soft beta rays of ^{14}C not detected by survey instruments; collect samples and smears for special low-energy beta counting in laboratory.
Cerium (Ce)	7.3.5.3–DTPA, Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.5.3–DTPA	See Section 6.3. Chelation should start as soon as treatment decision is made. CaEDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available.
Cesium (Cs)	7.3.2.6–Prussian Blue, Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.2.6–Prussian Blue	See Section 6.4. Ion exchange resins (7.3.2.5) should be as effective as Prussian Blue, but have not been used in humans.
Chromium (Cr)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	No treatment available for anionic forms, 7.3.5.3–DTPA or 7.3.5.6–DFOA for cations.	Antacids are contraindicated. Adsorbents (such as charcoal or MgO_2) may reduce intestinal tract absorption.
Cobalt (Co)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	See comment.	See Section 6.5. Penicillamine (7.3.5.5) may be considered for therapeutic trial in large exposures.

Curium (Cm)	7.3.5.3–DTPA Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.5.3–DTPA	See Section 6.6. See Section 7.2 for contaminated wounds. Chelation should start as soon as treatment decision is made. Ca-EDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available.
Europium (Eu)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.5.3–DTPA	
Fission Products (Mixed)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	Depends on major isotope(s) in mixture, which varies with age of the isotope mixture.	Gamma-ray spectroscopy of plant air or swipe samples may identify prominent radionuclide(s) in mixture to determine definitive therapy. Check also for possible alpha emitters. Most important nuclides may be iodine, cesium, cerium, and strontium.
Fluorine (F)	7.3.2.7–Aluminum hydroxide gel	See comment.	Very short half-life. Oral aluminum hydroxide gel will reduce absorption from gastrointestinal tract.
Gallium (Ga)	See comment.	See comment.	Short half-life. Penicillamine (7.3.5.6) can be considered for therapeutic trial.
Gold (Au)		7.3.5.4–Dimercaprol and 7.3.5.5–Penicillamine are possible therapeutic agents.	See Section 6.7. No known therapy for Au in colloidal form.
Hydrogen (H)			See Tritium.
Indium (In)		7.3.5.3–DTPA	Pharmaceutical form of indium is chelated already.

TABLE 2.5—*Continued*

The benefit from therapy recommendations in the Immediate Actions (Col. 2) and Drugs to Consider (Col. 3) columns will be influenced by the route of exposure—ingestion, inhalation, skin absorption, injection, or contaminated wounds. The chemical form and solubility of the radionuclide will also change markedly the efficacy of the recommended treatment. This table lists therapeutic procedures or drug therapy that may be helpful for the listed element in the favorable circumstances. The user is advised to consult the text for details on the influence of these other factors. The numbers in this table refer to sections in the text where additional information is available.

Element	Immediate actions[a]	Drugs to consider[a]	Information and comment
Iodine (I)	7.3.3.2–KI, Consider 7.3.2.2–Lavage	7.3.3.2–KI	See Section 6.8. Success of stable iodine (7.3.3.2) depends on early administration.
Iron (Fe)	Consider 7.3.2.2–Lavage and 7.3.2.10–Phytates	7.3.5.6–DFOA	Materials that reduce GI absorption include phytates (7.3.2.10), egg yolk, or adsorbents. Oral penicillamine (7.3.5.5) also chelates iron.
Lanthanum (La)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.5.3–DTPA	CaEDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available.
Lead (Pb)	Consider 7.3.2.2–Lavage	7.3.5.2–EDTA	Dimercaprol (7.3.5.4) and penicillamine (7.3.5.5) are less satisfactory alternative drugs.
Mercury (Hg)	Consider 7.3.2.2–Lavage	7.3.5.5–Penicillamine	See Section 6.9. Dimercaprol (7.3.5.4) may be considered for alternative therapy. Gastric lavage with egg white solution or 5 percent sodium formaldehyde sulfoxide; if unavailable, use a 2–5 percent solution of sodium bicarbonate.
Neptunium (Np)		See comment.	DTPA (7.3.5.3) may not be effective, but no other drugs are available.
Phosphorus (P)	Consider 7.3.2.2–Lavage and 7.3.2.7–Aluminum Hydroxide	7.3.3.4–Phosphates	See Section 6.10. Severe overdosage may be treated with parathyroid extract IM (7.3.4.6) in addition to oral phosphates (7.3.3.4).

Plutonium (Pu)	7.3.5.3–DTPA	7.3.5.3–DTPA	See Section 6.11. CaEDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available, but is less effective. Chelation should be started as soon as treatment decision can be made. Desferrioxamine (7.3.5.6) may be used initially if DTPA is not available. See Section 7.2 for contaminated wounds.
Polonium (Po)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.5.4–Dimercaprol	See Section 6.12. Consider toxicity of Dimercaprol before using in cases of low-level exposure. Penicillamine (7.3.5.5) is an alternative treatment.
Potassium (K)	Consider 7.3.2.4–Purgatives, 7.3.4.4–Diuretics, 7.3.2.7–Aluminum Hydroxide	7.3.4.4–Diuretics	Use aluminum hydroxide antacids first to reduce GI tract absorption. Use oral liquid potassium supplements (7.3.3.8) for dilution.
Promethium (Pm)	7.3.5.3–DTPA Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.5.3–DTPA	Chelation should be started as soon as treatment decision is made.
Radium (Ra)	7.3.2.4–Magnesium Sulfate Consider 7.3.2.2–Lavage and 7.3.2.4 –Purgatives	See comment.	See Section 6.13. Use 10 percent magnesium sulfate solution for gastric lavage and as saline cathartic. Oral sulfates (7.3.2.9) reduce intestinal absorption. No effective therapy after absorption. Ammonium chloride (7.3.4.3) and calcium (7.3.3.6) may increase urinary excretion slightly. Other agents that have shown little success include thyroid extract, parathyroid extract, and I.V. ACTH. Alginates are useful to reduce gastrointestinal absorption.

TABLE 2.5—*Continued*

The benefit from therapy recommendations in the Immediate Actions (Col. 2) and Drugs to Consider (Col. 3) columns will be influenced by the route of exposure—ingestion, inhalation, skin absorption, injection, or contaminated wounds. The chemical form and solubility of the radionuclide will also change markedly the efficacy of the recommended treatment. This table lists therapeutic procedures or drug therapy that may be helpful for the listed element in the favorable circumstances. The user is advised to consult the text for details on the influence of these other factors. The numbers in this table refer to sections in the text where additional information is available.

Element	Immediate actions	Drugs to consider	Information and comment
Rubidium (Rb)	7.3.2.6–Prussian Blue	7.3.2.6–Prussian Blue	Chemical properties are similar to potassium, but efficacy of similar treatments is unknown.
Ruthenium (Ru)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	See comment.	Chlorthalidone (7.3.4.4) causes enhanced urinary excretion. DTPA (7.3.5.3) has variable effectiveness.
Scandium (Sc)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	7.3.5.3–DTPA	EDTA (7.3.5.2) may be used in place of DTPA.
Silver (Ag)			Short effective half-life. No therapy.
Sodium (Na)	Consider 7.3.2.2–Lavage	7.3.4.4–Diuretic	Isotopic dilution (1 liter I.V. - 0.9 percent NaCl) by I.V. route followed by furosemide or other diuretic agents (7.3.4.4).
Strontium (Sr)	7.3.2.7–Aluminum Phosphate (7.3.2.4–Magnesium Sulfate or 7.3.2.8–Alginates are alternatives) Consider 7.3.2.2–Lavage	7.3.3.3–Strontium or 7.3.3.6 (Calcium I.V.) and 7.3.4.3 (Ammonium chloride)	See Section 6.14. Corticosteroid (7.3.4.7) may be considered, but adverse reactions should be balanced against probable limited effectiveness.

Sulfur (S)	Consider 7.3.2.2–Lavage and 7.3.2.4–Purgatives	No therapy known.	Soft-energy beta rays of ^{35}S not detectable with conventional survey instruments. A thin window survey meter may be used or obtain smears or samples for special low-energy beta counting in laboratory.
Technetium (Tc)			See Section 6.15. Potassium perchlorate has been used effectively to reduce thyroid dose.
Thorium (Th)		DTPA (7.3.5.3) or DFOA (7.3.5.6) useful for soluble compounds.	See Section 6.16. Treatment not effective for thorotrast (ThO_2).
Tritium (^3H)	7.3.3.5–Forced water	7.3.3.5–Forced water	See Section 6.17. Soft-energy beta rays of ^3H, not detectable by survey instrument, require samples for special low-energy beta counts in laboratory.
Uranium (U)	7.3.5.3–DTPA		See Section 6.18. DTPA must be given within 4 hours to be effective. Sodium bicarbonate protects kidney from damage.
Yttrium (Y)		7.3.5.3–DTPA	CaEDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available.
Zinc (Zn)	Consider 7.3.2.2–Lavage. Phytates (7.3.2.10) may reduce intestinal uptake.	7.3.5.3–DTPA	Zinc sulfate (7.3.3.7) may be used as diluting agent if CaDTPA is not immediately available. CaEDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available. Penicillamine (7.3.5.5) is a second alternative for DTPA.
Zirconium (Zr) –Niobium (Nb)	Consider 7.3.2.2–Lavage	7.3.5.3–DTPA	CaEDTA (7.3.5.2) may be used if CaDTPA (7.3.5.3) is not immediately available.

TABLE 2.6—*Information*

(1) Nuclide	(2) Radiation	(3) Rhm per curie	(4) Measurement methods	
			External	Internal
Americium-241	alpha, gamma	0.01	A, BG(SP), S	IVC, F, NS, U
Americium-243	alpha, gamma, D	0.02	A, BG(SP), S	IVC, F, NS, U
Arsenic-74	beta, gamma	0.42	BG, S	BC, NS
Arsenic-77	beta, gamma, D	0.006	BG, S	BC, NS
Barium-140	beta, gamma, D	0.14	BG, S	BC,N S, U
Cadmium-109	gamma, D	0	BG(S), S	F, U
Calcium-45	beta	—	BG, S	U
Calcium-47	beta, gamma, D	0.54	BG, S	BC, NS, U
Californium-252	gamma, alpha, neutron, D	—	A, BG, S	BC, U, NS
Carbon-14	beta	—	S(LS), BG(SP)	U, F, B(CO_2)
Cerium-141	beta, gamma, D	0.033	BG, S	BC, F, NS, U
Cerium-144	beta, gamma, D	0.008	BG, S	BC, F, NS, U
Cesium-137	beta, gamma, D	0.32	BG, S	BC, F, NS, U
Chromium-51	gamma	0.018	BG, S	BC, F, U
Cobalt-57	gamma	0.093	BG, S	BC, F, U
Cobalt-58	beta, gamma	0.54	BG, S	BC, F, U
Cobalt-60	beta, gamma	1.3	BG, S	BC, F, U
Curium-242	alpha, neutron, gamma	—	A, BG, S	BC, F, U
Curium-243	alpha, gamma	0.041	A, BG, S	BC, F, U
Curium-244	alpha, neutron, gamma	—	A, BG, S	BC, F, U
Europium-152	beta, gamma, D	0.53	BG, S	BC, F, U
Europium-154	beta, gamma	0.63	BG, S	BC, F, U
Europium-155	beta, gamma	0.021	BG, S	BC, F, U
Fission Products	beta, gamma	—	BG, S	BC, F, NS, U
Fluorine-18	beta, gamma	0.56	BG, S	BC
Gallium-72	beta, gamma	1.16	BG, S	BC
Gold-198	beta, gamma	0.23	BG, S	BC, F, U
Hydrogen-3 (Tritium)	beta	—	BG(SP), S(LS)	U
Indium-114m	beta, gamma, D	0.042	BG, S	BC
Iodine-125	beta, gamma	0.07	BG, S	BC, IVC, U
Iodine-131	beta, gamma, D	0.21	BG, S	BC, IVC, U
Iron-55	gamma	—	BG, S	F
Iron-59	beta, gamma	0.63	BG, S	BC, F
Lead-210	beta, gamma, D	0.002	BG, S	F, U, IVC

[a] See column explanations on page 18 and 19.

on selected radionuclides[a]

(5) Half-life		(6) MPBB μCi	(7) Critical organ[a]	(8) Dose (rem/μCi in organ)			
				Critical organ		Lung (Inhalation)	
Physical	Effective			13 week	50 yr	13 week	50 yr
458 yr	139 yr	0.05	Bone	190	30,000	250	2100
7950 yr	195 yr	0.05	Bone	180	30,000	240	2000
18 d	17 d	—	Total body	0.009	0.01	0.36	0.36
39 h	24 h	—	Total body	0.0004	0.0004	0.028	0.028
13 d	11 d	—	Bone	0.49	0.49	1.3	1.3
453 d	140 d	20	Liver	0.19	0.53	0.36	1.5
165 d	162 d	30	Bone	0.24	0.74	0.20	0.24
4.5 d	4.5 d	—	Bone	0.12	0.12	0.25	0.25
2.6 yr	2.2 yr	0.01	Bone	710	11,000	890	5100
5730 yr	12 d	—	Total body	0.0006	0.0006	0.14	0.20
32 d	30 d	—	Liver	0.29	0.23	0.36	0.41
284 d	280 d	5	Bone	3.7	16	5.1	17
30 yr	70 d	—	Total body	0.03	0.04	1.1	1.5
28 d	27 d	—	Total body	0.0006	0.0007	0.025	0.027
270 d	9 d	—	Total body	0.0009	0.0009	0.13	0.16
71 d	8 d	—	Total body	0.005	0.005	0.55	0.62
5.3 yr	10 d	—	Total body	0.015	0.015	1.9	2.6
163 d	155 d	0.05	Liver	180	540	230	580
32 yr	27.5 d	0.09	Liver	160	15,000	260	2100
17.6 yr	16.7 yr	0.1	Liver	160	11,000	260	2100
13 yr	3 yr	20	Kidney	3.8	69	1.4	11
16 yr	3 yr	5	Bone	1.8	34	3.7	29
2 yr	1.3 yr	70	Kidney	1.2	9.3	0.4	1.9
—	—	—		—	—	—	—
2 h	2 h	—	Total body	0.00007	0.00007	0.003	0.003
14 h	12 h	—	Liver	0.024	0.024	0.047	0.047
2.7 d	2.6 d	—	Total body	0.001	0.001	0.087	0.087
12 yr	12 d	—	Total body	0.0002	0.002		
49 d	27 d	—	Kidney, Spleen	5.6	6.2	1.6	1.7
60 d	42 d	—	Thyroid	4.2	5.4		
8 d	8 d	—	Thryoid	6.5	6.5		
2.6 yr	1 yr	1000	Spleen	0.19	1.2	0.016	0.023
46 d	42 d	—	Spleen	5.5	7.0	0.69	0.74
20 yr	1.3 yr	0.4	Kidney	150	1200	66	92

TABLE 2.6—

(1) Nuclide	(2) Radiation	(3) Rhm per curie	(4) Measurement methods	
			External	Internal
Mercury-197	gamma	0.037	BG, S	BC, U
Mercury-203	beta, gamma	0.013	BG, S	BC, U
Molybdenum-99	beta, gamma, D	0.076	BG, S	BC, NS, F, U
Neptunium-237	alpha, gamma, D	0.017	A, BG, S	BC, U
Neptunium-239	beta, gamma	0.05	A, BG, S	BC, U
Phosphorus-32	beta	—	BG, S	BC, U
Plutonium-238	alpha, gamma	0.001	A, BG(SP)	IVC, F, NS, U
Plutonium-239	alpha, gamma	<0.001	A, BG(SP)	IVC, F, NS, U
Polonium-210	alpha	<0.001	A	U, F
Potassium-42	beta, gamma	0.14	BG, S	BC, U
Promethium-147	beta	—	BG, S	F, U, NS
Promethium-149	beta, gamma	0.004	BG, S	F, U, BC, NS
Radium-224	alpha, gamma, D	—	A, BG	BC
Radium-226	alpha, gamma, D	0.825	A, BG, S	BC, B
Rubidium-86	beta, gamma	0.05	BG	BC, F, U
Ruthenium-106	beta, D	0.11	BG	BC, F, U
Scandium-46	beta, gamma	1.1	BG	BC, F, U
Silver-110m	beta, gamma, D	1.4	BG	BC, U
Sodium-22	beta, gamma	1.2	BG	BC, U
Sodium-24	beta, gamma	1.8	BG, S	BC, U
Strontium-85	gamma	0.3	BG, S	BC, U, F
Strontium-90	beta, D	—	BG, S	U, IVC, F
Sulfur-35	beta	—	BG(SP), S(LS)	F, U
Technetium-99m	gamma	0.059	BG, S	BC, NS, U
Technetium-99	beta	—	BG, S	U
Thorium-230	alpha, gamma	—	A, BG, S	BC, IVC, F, U
Thorium-232	alpha, gamma, D	—	A, BG, S	BC, IVC, F, U
Thorium-Natural	alpha, beta, gamma	—	A, BG, S	BC, IVC, F, U
Tritium (see Hydrogen-3)				
Uranium-235[b]	alpha, gamma, D	—	A, BG	BC, IVC, U
Uranium-238	alpha, gamma, D	—	A, BG	BC, IVC, U
Uranium-Natural	alpha, beta, gamma	—	A, BG	BC, IVC, U
Yttrium-90	beta	—	BG, S	U
Zinc-65	beta(+), gamma	0.3	BG, S	BC, U
Zirconium-95	beta, gamma, D	0.4	BG, S	BC, U

Continued

(5) Half-life		(6) MPBB μCi	(7) Critical organ[a]	(8) Dose (rem/μCi in organ)			
				Critical organ		Lung (Inhalation)	
Physical	Effective			13 week	50 yr	13 week	50 yr
2.7 d	2.3 d	—	Kidney	0.022	0.022	0.009	0.009
46 d	11 d	—	Kidney	0.30	0.30	0.30	0.31
2.8 d	1.5 d	—	Kidney	0.17	0.17	0.094	0.094
2×10^6 yr	200 yr	0.06	Bone	170	28,000	220	1800
2.3 d	2.3 d	—	GI(LLI)	0.023	0.023	0.027	0.027
14 d	14 d	—	Bone	0.10	0.10	0.56	0.56
88 yr	63 yr	0.04	Bone	190	26,000	250	2100
2.4×10^4 yr	197 yr	0.04	Bone	180	30,000	230	2000
138 d	46 d	—	Spleen	880	1100	120	150
12 h	12 h	—	Total body	0.00	0.00	0.056	0.056
2.6 yr	1.6 yr	60	Bone	0.22	2.2	0.29	1.7
2.2 d	2.2 d	—	Bone	0.044	0.044	0.071	0.071
3.6 d	3.6 d	—	Bone	11	11	70	70
1600 yr	44 yr	0.1	Bone	73	10,000	290	410
19 d	13.2 d	—	Total body	0.009	0.009	0.66	0.66
368 d	2.5 d	—	Kidney	0.80	0.80	5.6	22
84 d	40 d	—	Liver	0.64	0.70	1.3	1.5
255 d	5 d	—	Total body	0.008	0.008	3.3	0
950 d	11 d	—	Total body	0.018	0.018	0.0012	0.0012
15 h	14 h	—	Total body	0.0017	0.0017	0.0023	0.0023
65 d	65 d	—	Total body	0.014	0.022	0.30	0.33
28 yr	15 yr	2	Bone	3.6	320	2.9	4.1
88 d	44 d	—	Testis	22	40	0.00008	0.00008
6 h	5 h	—	Total body	0.00001	0.00001	0.00064	0.00064
2×10^5 yr	20 d	—	Kidney	0.12	0.13	0.09	0.13
8×10^4 yr	200 yr	0.05	Bone	160	29000	210	1800
1.4×10^{10} yr	200 yr	0.04	Bone	180	33000	210	1800
—	200 yr	0.01	Bone	180	33000	200	1700
7.1×10^8 yr	15 d	—	Kidney	170	170	200	1700
4.5×10^9 yr	15 d	—	Kidney	160	160	190	1600
4.5×10^9 yr	15 d	—	Kidney	170	170	200	1700
64 h	64 h	—	Bone	0.12	0.12	0.17	0.17
245 d	194 d	60 —	Total body	0.018	0.066	0.36	0.46
66 d	56 d		Total body	0.003	0.003	0.97	1.09

[a] See column explanations on pages 18 and 19.

[b] For measurement of enriched uranium exposures, the ^{234}U activity must be ascertained in addition to ^{35}U.

COLUMN EXPLANATIONS FOR TABLE 2.6

Information on selected radionuclides

Column (1) *Nuclide.* The name of the element and the atomic mass of the particular isotope are listed alphabetically by element.

Column (2) *Radiations.* The primary radiations are listed. For simplicity, some liberties have been taken in listing the radiations.

Beta refers to both positron and electron emission.

Gamma includes conversion x-ray emissions as well as gamma rays. The letter D refers to the possible presence of daughters with a half-life of less than 25 years. The radiations of the daughters are not included in the listing.

Column (3) *Rhm per Ci.* Roentgens per hour at 1 meter from 1 curie. These values are only approximate. A dash in the column indicates that the number was not evaluated because daughter radiations contribute appreciably to the gamma dose rate; because of an uncertain or complex decay scheme; or because the isotope emits no appreciable gamma radiation, as in the case of pure beta emitters.

Column (4) *Measurement Methods.* The following symbols are used to indicate principal techniques for measuring external contamination or indicating internal exposure. The order of the symbols has no significance in the listing.

External: A–Alpha counting techniques.
BG–Beta-gamma counting and detection techniques. Start all monitoring with detector unshielded.
BG(Sp)–Special attention necessary to select appropriate low-energy monitoring techniques.
S–Smear or swipe sample counted in laboratory.
S(LS)–Liquid scintillation counting of samples.

Internal: BC–Whole body count (standard gamma detection methods), including nuclear medicine counters.
F–Feces sample analyses.
IVC–Special in vivo counting techniques useful for low-energy counting, e.g., wound-monitoring, thyroid counting, or special low-energy x-ray or gamma detectors for chest counts, e.g., plutonium or americium counting.
NS–Nose swipe counted in laboratory if inhalation suspected.
U–Urine sample analyses.
B–Breath analysis for gases.

Column (5) *Half-Life.* The radioactive and the effective half-lives are taken from ICRP (1960), except for the transuranic elements which were taken from ICRP (1972).

Column (6) *MPBB.* The maximum permissible body burden (MPBB) is listed for those radioisotopes with effective half-lives in excess of 120 days. For isotopes with shorter effective half-lives, the estimated dose to the critical organ is more meaningful for emergency decisions (see Column 8). The MPBB is based on a life-time continued exposure under conditions in which an equilibrium is established, or at least approached between intake and elimination. It should not be used in the sense implied in this table for a single exposure situation.

Column (7) *Critical Organ.* The organ that receives the highest dose or has the most

significant biological effect. Only one organ has been listed for each radioisotope. This is an artificial representation since different chemical forms and modes of exposure will determine the critical organ; this table is intended to give only a limited presentation on one principal organ at risk until more complete information can be obtained.

Column (8) *Dose.* An approximate dose equivalent in rem is calculated for 1 microcurie of the radionuclide in the *critical organ* (Column 7) or lung, in the case of inhalation, after 13 weeks and 50 years residence time in that organ. These are approximate values to assist in rapid dose estimates if body (or organ) burden can be estimated. They are not definitive dose determinations particularly since they do not take into account the radionuclide distribution in the total body to the listed critical organ. Thus the physiological chemistry and solubility of the material involved in an actual exposure is not taken into account in this table. The curie for isotopes with radioactive daughters is defined as 3.7×10^{10} disintegrations per second of the parent only. Thus a curie of natural uranium includes only the activity of the ^{238}U parent and not activity of the daughter such as ^{234}U.

3. Initial Management of the Patient

3.1 Introduction

Physicians managing persons contaminated with radionuclides will have varying responsibilities depending on their primary roles, previous training, locations, facilities, and radiation monitoring capabilities. Even though definitive care may have to be given at some distant location, the immediate care and attention to details are extremely important.

An important question, which must be answered after a radiation accident, is whether any involved persons have been exposed to external or internal radioactive contaminants. To resolve this problem, radiation monitoring equipment must be available either at the accident location or the hospital. If a patient is suspected or known to be contaminated before he arrives at a hospital that does not have radiation instrumentation, the monitoring capability of the plant, public health, or civil defense authorities can be called on to assist in evaluating the extent of contamination. In the event that the contaminating event occurs at a facility licensed by the Nuclear Regulatory Commission, normal reporting procedures will invoke the response of the Nuclear Regulatory Commission consultants. Reporting requirements are described in the Code of Federal Regulations, Title 10 (CFR, 1978). The Interagency Radiological Assistance Plan (IRAP) is a program which organizes and trains radiological assistance teams throughout the United States to provide expert counsel and aid in accidents involving radioactive materials. Appendix A contains information and instructions on how to obtain help from the IRAP.

Initial decontamination and treatment decisions may have to be based on historical information, plus limited, or even superficial, radiological measurements. Evaluation of internal contamination may take days, or sometimes weeks, before a reasonably reliable estimate is achieved. The physician must proceed quickly to get the available information on the accident and evaluate the need for treatment based on the available estimates of exposure potential. Any risk in treatment

procedures must be balanced against the possible or presumed risk of the untreated exposure.

When the accidents are at nuclear plants or other large nuclear installations, the occupational physician should be prepared to render first aid and initial decontamination of patients at the plant, as well as to provide transportation of the victim to a nearby hospital. In some cases, complete on-site medical care and decontamination may be possible.

Accidental radiation exposures can occur at hospitals as a result of a misadministration of a radiopharmaceutical. A misadministration is defined as an administration of a radiopharmaceutical drug other than the one intended, to a wrong person, by a route of administration other than that intended by the prescribing physician, or with a dose, either diagnostic or therapeutic, that is significantly greater than prescribed. An adverse reaction should not be confused with a misadministration (Rhodes and Wagner, 1974). Adverse reaction refers to pharmaceutical properties of the radiopharmaceutical that produce symptoms relatively soon after administration.

Serious cases of misadministrations have been rare considering the millions of nuclear medicine procedures performed annually. Of three deaths reported in a U.S. General Accounting Office Report (1972), two resulted from confusion of microcurie (μCi) with millicurie (mCi) resulting in overdoses, and the other came from injecting soluble rather than insoluble colloidal ^{32}P.

Techniques described in this report may be helpful to treat a misadministration of a radiopharmaceutical in some cases. In addition to giving appropriate care and treatment, the physician-in-charge shall: (1) report the details of the confirmed misadministration to the hospital administrator and the appropriate medical staff committee; (2) seek expert consultation; (3) advise the patient or the patient's family of the circumstances; and (4) maintain detailed records.

3.2 Uptake and Clearance Mechanisms

Internal contamination occurs through three principal routes: inhalation, ingestion, and contaminated wounds. Percutaneous absorption is an infrequent route, tritium excepted, and is seldom a major concern. Accidental exposure to radionuclides through a syringe and needle, glass shards, or other puncture wounds may occur in industrial or research laboratories. Misadministration of radiopharmaceuticals can be a source of accidental internal exposures in hospitals.

Uptake and retention is influenced by the portal of entry, the chemistry and solubility of a compound, and its particle size. Some radioactive compounds may not be rapidly absorbed, even though considered to be relatively soluble, because of acidic or caustic properties that fix the material to tissue proteins.

After entrance into the body, a radionuclide will continue to irradiate the surrounding tissues until it is either excreted by some physiologic process, principally through the urine or feces, or removed by some treatment procedure, such as surgical removal of wound depositions, or until it becomes inactive through radioactive decay. The internal emitter will be metabolized according to its chemical properties. The metabolism of the radionuclide and its biologic half-life are as important as its physical half-life in determining the significance of the exposure. Some radionuclides, such as sodium-24, are distributed throughout the body as are the stable isotopes, e.g., sodium-25. Other radioisotopes, such as iodine-131, are concentrated in particular organs; in the case of the iodine, the thyroid becomes the principal organ involved, often called the "critical organ" because it receives a higher radiation dose or is the site of the most significant biological effect compared to other tissues. Table 2.6 lists only one critical organ for each radionuclide, an arbitrary and artificial limitation dictated by the size and scope of this report. More complete listings of critical organs for the radionuclides can be found in NCRP Report No. 22 (1959) and ICRP Publication 2 (1960). ICRP Publications 26 and 30 (1977, 1979) propose the use of weighting factors for the various organs of concern to calculate an effective whole-body dose instead of the critical organ concept presently used for radiation protection purposes.

If the radionuclide in question is not absorbed by the body tissues rapidly, knowledge of the transit and clearance times from the pulmonary and gastrointestinal tracts is essential for proper management of that internal contamination. For example, physiologic cleansing mechanisms, such as the mucociliary apparatus in the respiratory tract, may be effective in removing radioactive particles in the first few days after exposure. Table 3.1 shows the clearance times for insoluble particulates from various parts of the respiratory tract. This natural clearance pathway should not be overlooked in the initial evaluation of an accidental exposure.

Similarly, exposure of the gastrointestinal tract by intralumenal radioactive material depends largely on the transit time. Table 3.2 shows the mean emptying and occupancy times of the gastrointestinal tract. Ingestion exposures are rarely encountered from occupational exposures as a primary type of exposure, but all inhalation exposures

TABLE 3.1—*Clearance times of various branches of the human respiratory tract for insoluble particulates*[a]

Structural compartment	Clearance time[b] (hours)	Cumulative time[c] (hours)
Trachea	.1	.1
Bronchi	1.0	1.1
Bronchioles	4.0	5.1
Terminal Bronchioles and Alveolar Ducts	10.0	15.1
Alveoli[d]	100 to 1500+ days	100 to 1500+ days

[a] Morrow *et al.*, 1967; Weibel, 1963; ICRP, 1966 (Task Group on Lung Dynamics).

[b] Clearance time is the approximate time it takes a particle to traverse the particular respiratory tract compartment to the next compartment.

[c] Cumulative time is the approximate total time it takes a particle to traverse the particular compartment listed through the trachea and thus clear the respiratory tract.

[d] Particle size distribution will determine whether inhaled particles reach the alveoli or not.

TABLE 3.2—*Clearance times of the human gastrointestinal tract*[a]

	Mean emptying time[b] (hours)	Average occupancy time[c] (hours per day)
Stomach	1	6/24
Small Intestine	4	14/24
Upper Large Intestine	13–20	18/24
Lower Large Intestine	24	22/24
TOTAL	42 hours	

[a] Eve, 1966.

[b] Mean emptying time is the mean time required for material to pass through the listed segment of the gastrointestinal tract.

[c] This is the fraction of a day that material is physically present on the average in the various segments of the gastrointestinal tract.

have a secondary gastrointestinal component due to the mucociliary transport mechanism and swallowing.

The natural transit time in the gastrointestinal tract will vary widely with different individuals. A total transit time of 24 to 36 hours may occur in an active person who eats a high fiber diet and has adequate fluids, whereas a period of 5 days or longer may be experienced by a less active individual on a low fiber diet with a low fluid intake, and perhaps suffering from an abuse of laxatives. The transit time can usually be accelerated artificially with a purgative during the initial exposure period, but prolonged administration of purgatives to hasten transit of material cleared from the lungs is not indicated.

Absorption from the intestine varies widely with different elements and their chemical forms. For example, radioiodine is rapidly and completely absorbed whereas plutonium is almost not absorbed at all (0.003 percent) (Lanzl *et al.*, 1965). Unabsorbed alpha-emitting nuclides apparently do not cause gastrointestinal injury, even in large amounts (Sullivan *et al.*, 1960). Nevertheless, the gastrointestinal tract is the critical organ for many insoluble radionuclides that traverse it without appreciable absorption into the systemic circulation and other organs. The descending colon receives the greatest exposure since the gut contents normally remain there for about 75 percent of the total transit time through the gastrointestinal tract.

Such information can be of practical value, for example, in the interpretation of observations following the inhalation of a radioactive dust of unknown particle size and solubility. If the dust is highly soluble, some particles will rapidly enter the extracellular fluid compartment and thus be available for excretion via the urine within a few minutes to an hour with increasing quantities during the first 24 hours. If it does not appear promptly in sizable amounts in the urine, but elimination via the feces is high after 24 to 48 hours, it is probable that a significant portion of the material was relatively insoluble, and that some of the particles were large enough to be cleared from the tracheobronchial area of the lungs into the gastrointestinal tract. Because the amount retained in the alveoli cannot be readily estimated from such data, chest (whole body) counts are needed to make this determination for most gamma emitters (see Section 4.4). Whole body counts can be compared with the quantity of radioactive material eliminated via feces and urine to estimate the percentage of retention in the body.

3.3 The Contaminating Radionuclide

When an exposure to radioactive material has occurred, the first information received frequently will indicate which radionuclide(s) is involved or suspected based on the work the individual was performing and circumstances of the accident. Although skin decontamination should proceed promptly, the physician should determine the specific hazards and characteristics of the radionuclide before embarking on a vigorous internal treatment program. Although identification of the exact radionuclide obviously is important, it is often necessary to deal with the problem initially on the basis of knowing only that it is a "beta-gamma" or "alpha" emitter. In many instances, the exposure may be to mixed radionuclides that have predominantly "beta-gamma" or "alpha" radiations. One of the most important purposes in the

initial identification is to ensure that the instrumentation used can detect the radiations in question. Failure to recognize this problem can lead to underestimation of hazards, or even failure to detect any contaminants, until some later time when additional information becomes available. In order to handle intelligently the decontamination procedures, the physician should try to identify the exact isotope(s) involved and certain basic facts, such as the type of radiation it emits. Such identification can be done by spectrometry studies on the contaminants. A few properties of some of the more common radionuclides have been listed in Table 2.6 of the Quick Reference Section (Section 2) for use in early evaluation of an accident.

3.4 Initial Radioactivity Measurement

3.4.1 *Nasal Swabs*

As soon as the patient's condition permits, and prior to showering or washing the face, nasal swab samples for radioactivity should be obtained. The sample is collected on a moist, clean, cotton-tipped applicator or on filter paper on a swabstick (Section 4.1.4). Use a separate swab for each nostril and rotate it gently over the accessible surfaces. This sample should be taken by the health physics surveyor or nurse rather than the subject to avoid contamination of the sample by material on the hands or clothes. Applicators intended for counting alpha contamination must be dried since a film of water provides enough shielding to prevent reliable detection of activity. Each applicator should be put into a separate test tube or envelope labeled with the subject's name, sample collection time and date, and sent to a nearby laboratory counter where a radiation measurement can be made. Measurement techniques are discussed briefly in Section 4.1.4.

The presence of contamination in the nose, particularly if the reading is similar from both nostrils, is presumptive evidence of inhalation of the contaminant. For useful results, it is important to obtain the test prior to showering or blowing nose. Often when a patient showers he snuffles water into his nose and blows it out forcefully, a maneuver that may wash out most of the contamination. A low amount or absence of contamination in the nose must not be regarded as evidence of minimal internal contamination. The nasal swab will not be meaningful if taken some time later when the individual is seen by a physician. Only when it is taken immediately after suspected inhala-

tion, in the field at the site and before showering, can it be a useful guide.

The interpretation of measurements on nasal swabs is influenced by many factors. In explosions, a victim may gasp through his mouth as the shock wave passes and then hold his breath until he gets out of the room. The nasal passages may thereby have been bypassed. Particles deposited on the ciliated mucous membrane of the nasal passages are cleared from the nose relatively rapidly. Those deposited near the mucocutaneous junction will remain for 60 minutes or longer, but those 2-3 cm above the junction will be cleared and swallowed within 10 to 20 minutes (Hilding, 1959). Since nasal contamination can also occur if the victim rubs his nose with a contaminated hand, positive nasal swabs must be interpreted cautiously.

A rule-of-thumb judgment used by some health physicists and physicians in evaluation of nasal swabs after possible plutonium (alpha) inhalation is that a value greater than 500 dis/min indicates a possible serious exposure, while results less than 50 dis/min would suggest no more than a possible low order exposure. Exposures with a high value in one nostril and much lower, or none, in the other are suspect for contamination other than by inhalation. Nasal swabs are useful because of their early availability but they should always be followed by more definitive tests, such as *in vivo* measurements of radionuclides in the chest or whole body and urinary excretion measurements.

3.4.2 *Initial Survey*

After the initial decontamination procedures, the patient should be resurveyed for residual contamination. If possible, this should be done by a health physicist or someone experienced in the use of radiation survey instruments. The physician who has not had training and experience in their use should not depend on his own measurements. It is important to get accurate skin contamination estimates since the improper use of monitoring instruments could lead to gross underestimates or overestimates or even completely miss the contamination. The latter is more likely if the contamination is due to a low-energy beta emitter such as ^{3}H, ^{35}S, ^{14}C, or ^{147}Pm, or an alpha emitter such as ^{239}Pu or ^{210}Po. Except in cases of high-level contamination, over about one rad per hour including beta radiation, there is no urgency to complete skin decontamination.

If the patient is contaminated with beta- or gamma-emitting radionuclides, a quick body survey, often called a "frisk", can be accomplished with a Geiger-Mueller survey meter. A methodical search of

all skin surfaces should be made first with the shield open and areas of contamination circled with a felt pen. The patient then should be resurveyed with the shield closed to determine what proportion of the radioactivity is due to gamma (penetrating) radiations. The probe must be moved slowly so that low-level activity will not be missed.

A routine check for alpha contamination should always be made unless there is no possibility that it could be present. When the nature of the contaminant is unknown it is mandatory that an alpha survey be made. Estimating the degree of contamination of skin with a pure alpha emitter or a mixture of alpha- and beta-gamma emitters is often difficult because a small amount of water, perspiration, blood, serum, or tissue will shield out the alpha radiation. For this reason alpha contamination measurements, in particular, should be performed by experienced personnel.

The physician who has limited experience with radiation detection instruments should be aware of several rules-of-thumb. Counts per minute as detected by the instrument are not equal to the disintegrations of the radionuclide atoms per minute. Simple general conversions can be made by multiplying counts/minute (alpha) $\times$ 2 and counts/minute (beta-gamma) $\times$ 10 to be approximately equal to disintegrations per minute. Translation to curies can be made by remembering that 2.2×10^6 dis/min equals 1 microcurie or 2.2 dis/min equals 1 picocurie. On beta-gamma instruments (Geiger-Mueller type), 2500 counts/minute are approximately 1 mR/h. Many survey instruments are calibrated directly in mR/h.

Most radiation surveys are crude measurements and are intended only to give approximate levels and locations of the contamination. Initial surveys should be made with instruments that have a large window of 30 to 100 cm^2 area. These can determine the approximate location of the contamination rapidly. The radioactivity measurement will be averaged over the area of the window. The use of a small end-window probe may be advantageous to determine more precisely the location of the contamination and to make possible a more effective decontamination effort.

3.4.3 *Initial Estimate of Internal Contamination*

Rapid estimation of the amount of internal contamination is difficult or impossible when alpha or pure beta emitters are involved.

Although whole body counting (Section 4.4.1) is extremely useful in the eventual estimation of the amount of internal contamination, its value immediately after the accident may be limited. The usual pres-

ence of even a small amount of residual contamination on the skin or in the hair grossly distorts the evaluation. It is almost impossible immediately after the accident to get all external contamination removed, even with an extremely vigorous decontamination effort. Careful evaluation of the photon spectra taken by high resolution gamma-ray detectors (Ge(Li), intrinsic Ge) can be useful to distinguish surface contamination from internal depositions.

Urine and fecal specimens shall be collected routinely after the accident for radiological measurements and determination of excretion rates of the radionuclides, but the initial samples often present special interpretation problems. In fact, bioassay is likely to be of little help during the initial evaluation, say the first 24 hours. The results of initial fecal samples may be low or even less than the detection limits since samples taken soon after the exposure are likely to consist of material that was in the colon before the exposure. The initial urine sample is also suspect since it is subject to errors of possible external contamination. Also, the residual urine in the bladder prior to exposure dilutes the initial sample and the time for dissolution or redistribution of the radionuclide in the body may lead to a low initial value. Furthermore, several days may be required before fecal or urine measurements for some radionuclides become available from the laboratory. A few soluble isotopes, such as iodine or tritium, will behave in a sufficiently predictable fashion that the early bioassay results can be extrapolated to an estimated exposure with reasonably good reliability.

The decision to treat is based on a careful evaluation of the historical details of the accident, the nature of the contaminant, and the amount of contamination detected in the nose or on the skin. For example, high skin contamination levels especially around the face, or more importantly, high air counts in an occupied area, or over 500 dis/min of long-lived alpha material detected on the nasal swab, each suggests possible significant internal contamination. When long-lived alpha emitters, such as ^{239}Pu or ^{244}Cm, are inhaled, the decision to treat early with DTPA will probably have to be made on such fragmentary information.

When gamma-emitting radionuclides have been ingested or have been inhaled and sufficient time has occurred for some clearance from the lung into the gastrointestinal tract (one hour), detection of gamma activity over the abdomen or chest may be falsely interpreted as being due to surface (skin) contamination. Ingestion or inhalation should be suspected when skin decontamination procedures are ineffective in these areas.

In accidents that release fission products, radioactive iodine uptake

by the thyroid can be checked crudely by holding a beta-gamma survey probe over the thyroid. Peak thyroid uptake values will not be reached until about 12 hours after exposure (Ramsden *et al.*, 1967).

In criticality accidents, the exposure to neutrons will induce radioactivity such as activation of normal body sodium to form radioactive ^{24}Na. This gamma-emitting nuclide can be detected with survey instruments held over the abdomen with the patient doubling over the probe or by placing the probe in the armpit. Although relatively insensitive, the technique can be useful in screening the exposed from the nonexposed if numbers of persons are potentially involved. A reading of about 0.1 mR/hr on a Geiger probe results from an absorbed dose of about 15 rads from a criticality assembly (Hankins, 1968). This technique should be followed by more accurate measurements on blood and urine samples for ^{24}Na (Sanders and Auxier, 1962; Hankins, 1968) or hair samples for ^{32}P (Petersen *et al.*, 1961; Petersen, 1965; Petersen and Langham, 1966; Hankins, 1968) from which good absorbed dose estimates of fast neutron exposures can be made. Metal objects, e.g., gold or copper jewelry, dental fillings, buttons, cigarette lighters, pocket knives, etc., should also be measured for induced radioactivity if neutron exposure may have occurred. Some of the most important dose distribution information can be secured from such measurements after a criticality accident.

3.5. On-Site Management

3.5.1 *Introduction*

The on-site medical and health physics staffs at the plant should provide as much care as possible before the patient is transported to the hospital. Trained personnel and instruments are usually available and this expertise should be used rather than sending a patient to a hospital that is poorly equipped or ill prepared to handle this type of accident. In general, the hospital should be used only for definitive medical care. Ideally, the personnel at the in-plant facility will have removed all transferable radioactive material from the patient, estimated the probable severity of internal contamination, and provided emergency first aid for wounds before the patient is moved to the hospital.

The check list in Table 2.1 covers major action areas that concern the plant physicians and health physicists in responding to a radioactively contaminated accident at the plant site. Resorting to a "recipe"

for action after a radiation emergency occurs is as ill-advised as treating a diabetic patient in severe keto-acidosis by following a rigid treatment formula. Nevertheless, a check list of things to be done at the plant can be a valuable aid to the physician.

Since the plant physician's primary attention must be directed toward injured and contaminated victims, someone else, e.g., a designated emergency director, must be assigned the responsibility for management of the accident area. Access to the area shall be closed off and immediate surveys started to delineate the extent and severity of contamination and radiation levels. Ventilation, drafts, or air currents must be controlled to prevent spread of contamination. Film badges or thermoluminescent dosimeters must be collected from all persons involved, even though exposure to penetrating radiation is thought not to have occurred. A careful history of the location of each individual during the accident, his duties, his exit path, and where he went immediately after the accident is essential. It is important to know where each involved person can be contacted after leaving the plant site in case his dosimeter later reveals significant exposure, or if he is needed to corroborate or amplify details of exposure or injury to another person. The plant physician should relay his information on the accident to the physician-in-charge at the hospital and remain in contact with the hospital staff until the initial treatment decisions have been made.

The entire contaminated area should be roped off and radiation warning signs posted. An intermediate or transition zone should be established where individuals and articles leaving the contaminated zone are monitored and decontaminated as necessary. A clean zone should be established at the periphery within which persons are required to wear protective clothing and shoe covers. These operations should be supervised and directed by a health physics specialist if available. It is possible that a physician may have to organize the temporary contaminated area procedure until more supervisory help becomes available. The response to the potential offsite transport of radioactive materials through air or water contamination will be the concern of those responsible for public health and environmental safety.

3.5.2 *Emergency Plans*

Every plant, laboratory, and hospital that handles radioactive materials shall have a detailed emergency plan. The plan shall describe the emergency operating organization and define the lines of authority,

responsibilities, and functions of the assigned qualified individuals. Agreements shall have been made with local police and fire departments, ambulances, rescue squads, and hospitals so that all groups have clear understanding of their assigned responsibility in the event of a radiation accident. The availability and dependability of supplemental instrumentation and trained personnel are extremely important since available instruments and personnel will be in great demand after a large accident.

The plan should describe prior arrangements made with physicians, hospitals, and ambulance services for medical assistance and transportation of contaminated, injured, and exposed individuals. Without preplanning, inexperienced groups may be unwilling to assist because of an unreasonable fear of radiation injury to personnel or of radioactive contamination of equipment. The preplanning for the emergency response should include an annual exercise of the plan and audit of the effectiveness of the plan.

Consulting services should have been arranged and coordinated with local medical authorities. Before being licensed, all nuclear power facilities shall have developed a detailed radiation emergency plan. Smaller facilities can often use such emergency plans as a guide to developing their own or may be able to coordinate their plan with a neighboring power facility. In the event of a radiation emergency for which no emergency plan is operative, it may be helpful to contact the supervisor or health physicist of a nearby nuclear power facility who can identify physicians in the area capable of providing consultation and assistance.

3.5.3 *Immediate Care*

If workers have been seriously injured in the accident, immediate emergency medical care is obviously most important. When a life or death surgical emergency exists, the patient must receive immediate life-saving first aid and transportation to a hospital regardless of contamination, except as noted below. A hospital emergency room or surgical suite can always be decontaminated after its use in a contaminated case, although such cleanup may be expensive. It should be remembered, however, that skin or wound contamination is almost never immediately life threatening.

It is conceivable in an explosion that a worker could suffer a mangled extremity contaminated with embedded gamma-emitting foreign bodies such that the radiation level to the rest of the body and to first aid personnel could be an almost overriding consideration, e.g., gamma

levels of hundreds of rad/h. In such a case, if the general condition of the patient can be stabilized, emergency amputation or extensive surgical debridement performed at the site of the accident, in the nearest first aid station, or at a decontamination facility may be the only possible life-saving procedure. High-level contaminations of this magnitude provide the principal need and justification for gamma shields to protect persons engaged in decontamination work or surgery in radiological emergency centers (Section 3.5.5).

Whenever possible, partial or complete external decontamination of injured patients should be performed at the site before they are sent to a hospital. All contaminated work clothing should be removed. Uninjured persons can frequently decontaminate themselves but they must be given suitable instructions and must be carefully monitored by someone experienced with decontamination techniques and use of radiation survey instruments. If only localized areas of contamination, such as the hands or face, are involved, these should be cleaned up by washing the area with detergent and water. In cases of more generalized contamination, the person is instructed to shower or, if not ambulatory, he should be thoroughly washed with soap or detergent. Often an initial shower can be given near the accident site and the patient then moved to an emergency medical and decontamination area where more elaborate skin decontamination techniques (Section 7.1) can be used. In most cases, radiation levels can be reduced sufficiently so that patients can be managed with but a few precautions at the hospital.

Unless the accident victim has serious injuries or the inplant facility is poorly equipped or staffed, there is usually no need to move the patient immediately to a hospital. Even with fairly serious injuries, it is better to stabilize the patient's physical condition and remove all easily transferable contamination than to rush him to a poorly prepared hospital. See Section 3.6 for details on transportation of patients.

3.5.4. *Public Relations Responsibilities*

The plant manager and the responsible public relations person should be apprised as soon as the potential consequences of the accident have been determined. The family of injured persons should be notified and briefed on the seriousness of the situation before a general news release is made. This notification should be made by the person(s) designated by the plant management and the personnel director. The families should have continued access to information from the medical authority (or designated company representative) as to the progress of treatment and recovery of the patients.

A prompt, accurate press release generally prevents unreasonable speculation by the news media. The press must be advised that initial evaluation of an internal contamination incident is difficult and may take days. The press's cooperation should be solicited and appropriate information released as soon as possible. A continuing effort to keep the news media informed as to the nature of the work at the plant may forestall an unfavorable news release at the time of an accident.

It is important to have only one person authorized to give information to the news media. A public relations person should be appointed this responsibility by the plant management. If the public relations person performs this task, all news releases should be reviewed for technical content and approved prior to issue by the attending physician, the company medical director, and the health physicist in charge of dosimetry.

3.5.5 *Decontamination Facilities*

Elaborate inplant decontamination facilities have been constructed at several locations (Norwood and Quigley, 1968; Norwood, 1964; Voelz, 1967; Finkel and Hathaway, 1956). Modest facilities which have a dual function are more practical for smaller plants (Holland, 1969). Emergency decontamination facilities can usually be planned or even improvised in a "change" room, locker room, or shower facility. The one essential feature is a shower or a bathtub. Access from more than one side is a useful convenience. Designed decontamination facilities are characterized by: (a) convenient equipment to wash both ambulatory and injured persons; (b) portable or permanent shielding for use in treating persons with high-level beta-gamma activities; and (c) a floor plan that will permit convenient decontamination work with a minimal opportunity for cross contamination of clean areas in the building. Supplies for the decontamination room, which ideally should be stored ahead of time, are listed in Table 3.3. When necessary, it may be possible to have them collected from other areas in the plant and brought immediately to the room.

If possible, before the contaminated person arrives at the decontamination facility, the floor should be covered with wrapping paper, the area isolated, all nonessential items removed from the room, and the staff dressed in scrub suits (see Table 2.4). Coveralls are also useful especially while the easily transferable contamination is being removed. Gloves and shoe covers should have been donned before the contaminated patient is admitted to the room. Respirators should be easily available and worn if significant transferable contamination

TABLE 3.3—*Decontamination room supplies*

1. Coveralls or surgical scrub suits.
2. Plastic aprons.
3. Surgical caps.
4. Plastic or rubber gloves.
5. Sterile surgical gloves.
6. Sterile suture sets with additional sterile scissors (2), forceps (4), scalpel (1), and hemostats (6).
7. Sterile irrigation sets.
8. Sterile applicators and miscellaneous dressings.
9. Clean long patient gowns or coveralls, socks.
10. Plastic shoe covers.
11. Large towels.
12. Safety razor with extra blades and aerosol shaving soap.
13. Bandage scissors (2).
14. Large plastic or cloth bags for collection of contaminated clothing.
15. Respirators (prefit for team personnel).
16. Radiation tags.
17. Radiation area signs, "Do Not Enter".
18. Personal dosimeters (ionization chamber, self-reading type; 200 mR and 20 R levels) and dosimetry badges (TLD type).
19. Masking tape, 2 inches wide.
20. Labeled containers for collecting urine and fecal specimens.
21. Blankets.
22. Adhesive labels and tags for labeling tissue or contaminated material.
23. Specimen bottles (with formalin if freezing facilities are not available).
24. Felt pens (black and red).
25. Note books, papers, pencils.
26. Portable beta-gamma survey meters. Include low range (up to 25 mR/hr) and high range instruments (up to 500 R/hr).
27. Portable alpha scintillation detector.
28. 1 large roll 36″ white absorbent (blotter-type) paper or wrapping paper as used in stores. (Tear-off dispensers are available for convenient storage and use of paper rolls.)
29. Plastic sheets.
30. Specific decontamination supplies: detergents primarily, others include titanium dioxide (abrasive), potassium permanganate (and sodium acid sulfite to remove stain), and household bleach (5 percent sodium hypochlorite) (Section 7.1). These items, along with simple instructions on their use, should be in a specific labeled box.
31. Fiberboard barrels or large waste baskets for disposal of contaminated clothing as well as other contaminated items.

(especially alpha emitting) is anticipated. The decision on the need for respirators will depend on the team leader's assessment of the extent of contamination of clothing and skin areas, the lack of cleanup of loose contamination prior to decontamination facility entry, and the advice of a health physicist knowledgeable about the accident conditions. Unless the room has a separate air conditioning or ventilation

system equipped with ultrafilters, the ventilation system should be shut off temporarily until the extent of transferable contamination has been determined and controlled. At the plant, where contamination levels may be high, all wash water should empty into a special process drain for radioactive contamination disposal or into holding tanks. Inability to divert wash water from the domestic sewer system should not be permitted to delay or retard the decontamination effort in an emergency since dilution factors will probably be adequate to reduce the hazard to insignificant levels in the final sewage effluent.

3.5.6 *Concomitant Exposure to Penetrating Radiation*

The most serious injuries resulting from radiation accidents have been due to penetrating radiation from external sources. In any radiation emergency it is important to evaluate whether significant external exposure may have occurred. In some cases a review of the circumstances of the accident may be sufficient to rule out this possibility. Results from film badges or thermoluminescent detectors exposed at the accident will provide more definitive data and should be recorded as soon as possible.

In some instances an exposure to external radiation may not be known or even suspected. If personnel dosimeter results are not also available, the clinical condition of the patient may provide the first evidence of significant external exposures.

Patients who develop nausea and vomiting in the first 24 hours after the radiation accident should be hospitalized. Since nausea and vomiting rarely occur as an emotional reaction to a radiation accident, they should be considered indicative of a serious exposure to penetrating radiation until proved otherwise. A white blood cell count (total and differential) should be performed promptly and then every 3–12 hours. If the counts reveal a rapid fall or a low value in absolute lymphocyte count within 48 hours, radiation injury is suggested strongly. Other laboratory diagnostic techniques, such as chromosome analysis, are useful (Thoma and Wald, 1959; Andrews, 1962; Bender and Gooch, 1962; Evans, 1967).

3.5.7 *Notifying the Hospital*

The hospital should be notified as soon as it has been determined that the patient may require hospitalization. Initial decontamination procedures and preliminary evaluations at the accident site may take several hours but advance notice during this time will enable the

hospital to mobilize its resources. The in-plant personnel must transmit all their information to the hospital staff and remain in communication until all early diagnostic and treatment decisions have been made. Names and points of contact of work associates and supervisors must be obtained for reference, even after the accident victim(s) has been transferred to the hospital, in case further information on details concerning the accident is needed.

3.5.8 *Collection of Excreta*

On completion of the initial first aid and preliminary clean-up procedures, the patient should void all his urine into a clean container carefully labeled with name, date, and time of collection. The collection must be performed with great care to prevent accidental contamination of the specimen with transportable contaminants on the hands, skin, clothes, or surroundings. Before the specimen is collected all contaminated clothing shall have been removed and the patient showered and his hands cleansed of transferable contamination. Use of disposable plastic gloves during sample collection may also be helpful in avoiding contamination of the sample. Each subsequent voiding shall be collected in separate containers until the initial evaluations are completed and the need for further samples has been determined.

Whenever possible after a contamination accident all feces should also be collected. Use of a large plastic bag placed in a cylindrical ice-cream type carton, or a large jar with a tight fitting lid, makes a convenient collection vessel. The use of a portable camping toilet is convenient for sample collection. Label samples with name, date, and time of collection. Samples may be refrigerated or frozen for preservation.

At the time of the first collection of excreta, the patient should be advised why it is necessary to collect *all* subsequent urinary and fecal excretions until notified to the contrary. He must be provided with containers and instructed on proper labeling with name, date, and time if he is not admitted to the hospital. If samples are being collected at the hospital, these special instructions should be reviewed in detail with nurses and floor attendants.

3.5.9 *Saving Other Contaminated Materials*

Sponges, applicators, and instruments that have been used to probe or cleanse any contaminated wounds should be kept in separate containers identified as to source and sequence. Each excised tissue

specimen should be monitored for radioactive contamination, put in a clean separate container, and frozen, if possible. If freezing is not available, specimens may be put into fixatives normally used for surgical pathology specimens.

In most cases, the amount of readily removable radioactive contamination on the skin or in the wound site, especially when initial decontamination has been done at the plant facility, is too small to justify holding the wash water for special analysis and disposal.

3.5.10 *First Aid After Internal Contamination*

Simple expedients such as oral and nasopharyngeal irrigation, gastric lavage, or an emetic and the use of purgatives may greatly reduce the uptake into the circulation. Blocking agents or isotopic dilution can appreciably decrease the uptake of radionuclides into stable metabolic pools such as the bone, from which it is not possible readily to mobilize the radionuclide. In general, blocking agents reduce absorption for less soluble or less active chemical compounds or saturate a target organ with a stable isotope. Isotopic dilution is an attempt to saturate the involved system of the body with the stable isotope in order to reduce proportionately the absorption or retention of the radioisotope. In order to be effective, these agents must be given as soon as possible after the contamination. The physician at the site of the accident should therefore administer them without delay or, if not available, he should contact the hospital and suggest their administration as soon as the patient arrives.

Specific recommendations on blocking agents or isotope dilution techniques are discussed in Section 7.3. Use of Table 2.5, Treatment Summary for Selected Elements, in Quick Reference Section 2 provides a rapid means of finding the appropriate agent to use for a particular exposure.

3.6 Transportation

Contaminated accident victims can be transported to a hospital or other medical facility in conventional ambulances. The removal of contaminated clothing and initial skin decontamination at the accident site will eliminate most of the readily transferable contamination. In transportation accidents where no on-site decontamination is possible, placing the victim in a sheet or blanket and covering the litter and

surrounding floor with plastic sheeting should prevent serious contamination of the ambulance or its attendants in most cases. Plastic coverings around the individual may cause excessive sweating and be uncomfortable; they should be used only under the patient and must not be used as a covering. Wrapping the patient carefully in clean sheets taped together to form an improvised bag will be adequate. Special commercial patient carriers or containers have been designed for transportation and decontamination of patients. If the ambulance does become contaminated, it can be decontaminated subsequently.

When the beta-gamma contamination on the skin or in wounds presents a significant hazard to ambulance attendants (several R per hour or higher), special precautions may be necessary. In many ambulances three to six feet separate driver and patient. Such a distance reduces the exposure to the driver and the attendant, if he remains up front with the driver, to a fraction of the dose that he would receive by being close to the patient. Exposures to passengers in other vehicles passing the ambulance on the highway would not be significant because of the shielding of the ambulance and other vehicle, the distance, and the short time of exposure.

If it is necessary to transport patients beyond the local area, the advantages of using an airplane or helicopter should be considered. Here again it is clearly advantageous that preliminary clean-up of transferable contaminants be done to the extent that the patient's medical injuries permit. If the majority of loose contamination is removed at the site of the accident, contamination of the aircraft, if any, should be minor and readily removable.

3.7 Hospital Management

3.7.1 *Introduction*

The Emergency Room physician at the hospital may receive patients who come from industrial facilities staffed with a wide variation of inplant medical and radiation protection capabilities. In some cases the hospital staff may find prompt and elaborate help available with historical and exposure information, medical advisors, radiation instrumentation, and health physics assistance. In others, only extremely modest help, if any, will be offered. The importance of preplanning at the hospital cannot be overemphasized (Saenger, 1963; Love, 1964).

When persons are involved in off-site transportation accidents, emergency room physicians can expect almost no immediate technical

support. The police or highway patrol will, at best, have limited capacity to assess radiation hazards and local public health or civil defense assistance may take some time to mobilize. Radiological assistance teams (see Appendix A for details of how to obtain help) can be consulted, and advice quickly given by telephone, but they will require some time for travel to provide on-site consultation.

Since the patient who is contaminated with radionuclides seldom has adequate information as to the radionuclides involved in the accident, the individuals who do have this information should be contacted as quickly as possible. When accidents occur after working hours or on weekends, collection of this information becomes difficult. At such times the supporting staff at the industrial facility or laboratory will be fewer in number and may not be as technically proficient as during regular hours.

3.7.2 *Hospital Pre-emergency Planning*

It is essential that the hospital emergency plan be prepared in advance for proper management of radioactively contaminated patients. See Table 3.4 for planning guidance. The medical and nursing staff should be trained in the basic principles of decontamination and radiological safety. If the accident involves contamination, the team should be prepared to monitor patients, personnel, equipment, and the area in addition to performing the appropriate decontamination procedures. If the accident involves direct external radiation without apparent radionuclide contamination, monitoring capability is still needed to rule out the possibility of contamination.

3.7.3 *Hospital Decontamination Facilities*

Ideally, decontamination facilities should be preplanned, but in the absence of planning, other arrangements can be improvised. An autopsy room is often the first choice as an emergency decontamination facility in a hospital. The autopsy table is easily adapted for washing a contaminated patient. The room is generally away from heavy hospital traffic and can be isolated easily. The furnishings are usually spartan so the cost of decontamination, if it becomes necessary, should be modest both as to replacement of items and interruption of services. In some hospitals, the physiotherapy, cast, or other rooms are better choices.

When an unprepared hospital emergency room receives a probably

TABLE 3.4—*Planning considerations for hospital management of the radioactively contaminated patient*

- Assemble hospital team of staff persons trained to manage contaminated radiation cases, including physicians, medical physicists, technicians, and nurses. A team leader shall be designated. Develop a list of consultants for advice—include physicians and health physicists experienced in handling such problems. These persons can aid the physician in charge of the case as needed.
- Use preselected area in hospital that is suitable for decontamination of patients—consider location of room in an area of the hospital having a nearby outside entry, showers, hot and cold water, floor drains, ease of room washdown, table suitable for washdown, and isolation of air movement thru air conditioning or heating system. Consider autopsy room, physiotherapy room, cast room, or regular emergency room as possible candidates unless a special decontamination room is available.
- Plan to evaluate the patient's medical condition immediately so as to determine priority of need for medical or surgical treatment, important diagnostic procedures, and decontamination procedures.
- Plan to move patient within the hospital as little as possible so as to minimize hospital contamination. Keep patient in selected work area for medical and minor surgical treatment until loose contamination has been removed.
- Arrange to have health physicist monitor area entrances and hallways after the patient is located in the room so as to prevent "tracking" to other hospital areas.
- Be prepared to set up monitoring station(s) at exits from the work area. Personnel should not leave the room (area) unless monitored for radioactivity. Equipment or property should not be removed from the room unless monitored. Designate persons to perform these monitoring tasks at specific locations.
- Prepare a list of decontamination room supplies (Table 3.3) and either store them in the room or identify where they are available for quick assembly.

contaminated patient, the staff should isolate the patient as if he had a contagious disease until the level of contamination has been determined. Spread of radioactive contamination can be reduced by requiring the attending staff to wear scrub suits, caps, gowns, and booties that are removed and placed in a plastic bag before leaving the area. Radiological monitoring should be performed on personnel and equipment before they leave the area.

3.7.4 *Decontamination of the Patient*

Before the patient arrives, the room designated as a decontamination facility should have had the floor covered with paper, preferably absorbent blotter-type or wrapping paper. This work area, where the contaminated patient is located and where contaminated materials are collected, shall be designated as "dirty." All other supporting work areas shall be kept "clean," if possible. Table 2.4 contains a check list

of suggestions and procedures for protection of personnel and hospital property from unnecessary contamination.

Thorough washing of the patient with soap or detergent and judicious scrubbing are the main ingredients of skin decontamination. Details of the skin decontamination procedures are given in Section 7.1 and wound decontamination procedures are covered in 7.2. Administration of blocking or isotopic diluting agents should be re-evaluated at this time.

At hospitals, where levels of transferable materials are usually lower because of prior decontamination efforts, wash water can usually be allowed to drain into sanitary sewerage systems. The regulations regarding disposal of radioactive materials into sanitary sewerage systems are found in The Code of Federal Regulations, Title 10, Part 20.303 (CFR, 1978).

3.8 Evaluation of the Contaminated Patient

3.8.1 *History*

Although first aid and emergency decontamination receive first attention, a detailed history must be obtained from the patient as soon as he can respond to questioning. A meticulously detailed record of exactly what happened is essential. If little information accompanied or preceded the arrival of the patient, the Medical Information Check List (Quick Reference Section, Table 2.3) can be used for interrogation of the patient and his associates present at the time of the accident, and others who may be knowledgeable about the materials involved. Some of the collection of this information can be delegated to a qualified radiation safety officer or health physicist. Too often historical details are relegated to a less important role because of the overdependence on physical measurements. Because of the difficulty in assessing the amount of internal contamination with alpha emitters, the decision to give a chelating agent such as DTPA may depend on the historical evaluation and interpretation of the accident. Often many details must be supplied by supervisors, health physicists and emergency personnel, but the patient's own story may be critical in determining how to proceed with therapy. This record, subsequently, may become an important legal item with reference to all parties, including the physician in charge.

If health physics assistance is available, try to get as specific information as possible. Be cautious about interpretations based on gross

radioactivity measurements because they can be misleading, particularly if the specific isotopes are not known. Specific isotope determinations are necessary for meaningful interpretation.

Because the evaluation of internal contamination will continue for days and weeks, a careful general medical history should be documented in writing or on a tape recorder while the details of the accident are fresh. In addition to a description of the accident and chief complaint(s), it is advisable to record a medical history review by systems and the patient's past medical history that includes previous accidental radiation exposures, both external and internal. The radionuclides that were involved and reliable sources of detailed information should be recorded. If put on tape, the information should be transcribed, dated, and initialed by the secretary and the physician.

Previous history of radiation therapy and any previous use of radioisotopes for diagnostic or therapeutic purposes should be recorded. The presence of chronic respiratory disease may reduce clearance of radioactive particulates from the lung so the history of respiratory disorders should be documented (Creasia and Nettesheim, 1972). In anticipation of possible use of chelating agents, any history of chronic renal disease and its current treatment should be recorded. History of past thyroid disease may be important in cases of radioiodine exposure.

3.8.2 *Physical Examination*

There are usually no physical findings after inhalation or ingestion of radioactive materials unless the chemical compound containing the radionuclide is toxic. The exact location of all wounds should be described. The general physical examination should be complete to determine physical findings of unsuspected or known disease states. A careful examination is important since the status of other health problems at the time of the internal contamination may assume medicolegal significance some time in the future. Whenever possible, color photographs of injuries that may be associated with an internal or external contamination are desirable; scars and residues of other lesions present before exposure should also be photographed and so labeled.

3.8.3 *Laboratory Tests*

A complete blood count, including platelets, and routine urinalysis should be performed. Instructions should be given to save all urine,

feces, vomitus, wound dressings, etc., for possible radiological analysis (see Sections 3.5.8 and 3.5.9). If there has been an external exposure to penetrating radiation (Section 3.5.6), repeated white blood cell counts will be necessary (Thoma and Wald, 1959; Andrews, 1962). The time and date of each blood count should be recorded. Chromosome analysis of peripheral blood lymphocytes is a useful aid for dosimetry (Bender, 1969). Techniques and instrumentation to measure radioactive contaminants are discussed in Section 4.

3.9 Public Health Considerations

Management of environmental contamination is not usually a responsibility of the physician who takes care of a patient contaminated with radionuclides, but he does have an obligation to notify persons who have this responsibility.

In plants operated under license of the U.S. Nuclear Regulatory Commission (NRC), health physics and environmental monitoring capability are required. Their managements have the responsibility to report accidents to the NRC. If environmental contamination is believed to be present, based on the history of the accident and findings in the patient, the physician need only notify a responsible person in plant management. When transportation accidents have occurred, the local public health authority must be notified.

4. Diagnostic Techniques to Measure Radioactive Contamination

The physician usually does not become involved in monitoring for radioactive materials. He should rely heavily on health physics specialists or medical physicists for measurements and dose calculations unless he has specialized training and experience. He should be familiar with the various techniques, however, in order to understand their reliability, limitations, and sources of potential error.

A summary of common radiation monitoring instruments and techniques is compiled in Table 4.1. More detailed descriptions are available in selected references (NCRP, 1978b; NCRP, 1978c; Healy, 1970; Hurst and Turner, 1970; Morgan and Turner, 1967; Shapiro, 1972).

4.1 Surface Contamination Measurements

The initial measurements made after most accidents determine possible external or surface contamination. The presence of radioactive contaminants indicates a possibility of internal uptake of these contaminants and also possible spread of the contaminants. These survey measurements are usually made in terms of either beta-gamma or alpha emitters, or both, rather than specific radionuclides.

4.1.1 *Alpha Monitoring*

Alpha radiation does not have sufficient penetrating power to pass through the epidermis and therefore alpha-emitting radionuclides are hazardous only when taken into the body. Surveys for alpha radiation are made to detect contamination that subsequently could be assimilated into the body by inhalation, by ingestion, or by absorption through wounds, but rarely through intact skin to any significant degree.

The low penetrating power of alpha particles dictates a detection

TABLE 4.1—*Common radiation measurement techniques and instruments*

Technique	Common name	Detector system	Major use	Special comments
1. Surface Monitoring—Alpha (α)				
a. Portable Air Proportional Counters		Air ionization	Field monitoring (alpha)	Area counted must be dry. Must measure very close to surfaces. Many sources of error.
b. Portable Gas Flow Counter with Probe		Gas (propane) ionization	Field monitoring (alpha)	Flammable gas. Also see 1.a comments.
c. Portable Scintillation Type Alpha Meters		Thin ZnS crystal	Field monitoring (alpha)	Light leaks cause false high readings. Also see 1.a comments.
2. Surface Monitoring—Beta/ Gamma (β, γ)				
a. Portable GM Count Rate Meter	GM (Geiger-Mueller) Meter or Counter	Geiger-Mueller discharge tube	Most common beta-gamma field instrument for determination of count rates—especially for low dose rates (e.g., below 20 mR/h)	Start surveys with shield open to detect betas and gammas total. False low readings may occur above design dose rate range. Will not detect very low-energy beta.
b. Portable Ionization Chamber Meter	Cutie Pie, Radector, Juno	Air or gas ionization	Common beta-gamma field instrument for determination of count rates—especially higher dose rates	Accurate dose rate meter.
c. Portable Scintillation Type Beta-Gamma Meter		NaI(Tl) crystal	Low-level search for gamma, x-ray or beta emitters	Good sensitivity but usually energy dependent.
d. Tritium Detector	Sniffer	Air conductivity meter	Detects presence of gaseous tritium or tritium vapor	Nonspecific, will react to smoke and other ions unless front end electrostatic precipitator eliminates them.
3. Laboratory Counters				
a. Gas Flow Proportional Counters		Gas ionization	Measures alpha, beta, or gamma on samples or filter papers and swipes, etc.	
b. Scintillation Counters	a) Well-Counters or	NaI(Tl)	Identification and measurement of low-level gamma emitter in samples	
	b) Gamma-Spectrometry	NaI(Tl) or Ge(Li) crystal		

TABLE 4.1—*Continued*

Technique	Common name	Detector system	Major use	Special comments
c. Liquid Scintillation Counters		Liquid scintillation	Measures low-energy ^{3}H-beta, ^{14}C, etc. or alpha	Care must be taken to see that impurities do not quench scintillations. Can be used as a spectrometer.
4. Smear or Swipe Test		Laboratory counters	Used for loose radioactive contaminants difficult to detect with field instruments—alpha, low-energy beta	Care must be taken to avoid cross contamination of samples. Not quantitative.
5. Nose Swipe (or nose blow)		Laboratory counters	Possible inhalation of alpha radionuclides	Should be collected before showering.
6. Urine monitoring		Laboratory counters	1) Whole sample for gross gamma or gamma spectrometry 2) Chemical preparations needed for beta counts or alpha spectrometry 3) Fluorometric chemistry for Uranium	Spectrometry should be done whenever possible rather than gross counts which can be misleading. On gross count for beta, ^{40}K will register strongly.
7. Feces monitoring		Laboratory counters	1) Whole sample for gross gamma or gamma spectrometry 2) Chemical separations needed for beta counts or alpha spectrometry 3) Indirectly measures potential inhaled (insoluble) radioactive particles	Spectrometry should be done whenever possible rather than gross counts which can be misleading. High residues after dissolution will mask significant alpha activity due to self-absorption. Samples should be taken first few days after inhalation exposure.

8. Personnel Monitoring Devices				
a. Photographic Film	Film badges	Film	1) Measures external radiation-penetrating gamma and frequently beta and soft gamma	Avoid leaving badge in contaminated clothes pile in emergencies. Must be developed by the issuing dosimetry service for best accuracy.
			2) Badge may include special neutron film	Detects fast neutrons, not the entire spectrum of energies.
b. Thermoluminescent	TLD	LiF or other crystals	Measures external radiation-penetrating gamma and may have beta and some neutron capability	Same as for film badge (8.a).
c. Pocket Ionization	Pencil chamber	Ionization chamber	Measures external radiation; may be a self-reading type or one requiring a reading device	May err on high side due to leakage, but low or no readings can be trusted.
9. Whole Body (In vivo) Counters		NaI crystal(s), liquid or plastic scintillators	Identifies gamma-emitting radioisotopes in the body and their quantity	1) Designed for low levels and may block out high levels.
10. Special In-vivo Counters				
a. Low Energy Chest Counter for Plutonium/Americium	Lung counter	Thin NaI crystal or Special CsI/NaI crystals (phoswich) or Special proportional counters	Measures plutonium x ray (17 keV) or americium gamma ray (60 keV) in or on the chest	Samples of air filters or smears from the accident will help determine Am/Pu ratios. Not useful if patient has gamma isotopes present also.
b. Plutonium Wound Monitor	Wound Counter	Thin NaI(T1), germanium (Li), or silicon (Li) crystals; silicon avalanche detectors	Measures plutonium x ray (17 keV) in wound to 1–2 cm depth	Not useful if elevated beta-gamma levels present in the wound area.
c. Thyroid Counters		NaI crystal	May be useful as an emergency whole-body counter for larger gamma exposures even without background shielding	Must be calibrated for the particular isotope(s) involved.
d. Anger Camera or Scanning Equipment		NaI crystal	Should be useful as an emergency whole-body scanner for gamma emitters	Must be calibrated for the particular isotope(s) involved.

instrument that has minimal absorbing material between the detector and the alpha source. The instrument window must be very thin (a few mg/cm^2 at the most) and the survey must be made as close as possible to the contaminated surface without contaminating the probe by physical contact. Fluids, such as water or blood, on the surface preclude a reliable alpha survey, and material embedded in a wound obviously cannot be detected by alpha measurement techniques.

An air proportional counter is the instrument most often used for alpha surface measurements, although gas-flow proportional counters or scintillation counters are also satisfactory. These instruments are designed to count alpha particles and discriminate against beta and gamma radiations.

False counts may occur on these instruments for many reasons. The air proportional counters are susceptible to errors due to vibration of the detector head, failure to adjust voltage properly, interference from electrical fields, high humidity, and vapors of alcohol or organic solvents. Damage to the probe window can cause erratic performance, although small leaks may not seriously degrade performance. Scintillation-type probes will give false high readings as a result of even a pinhole leak in the thin window due to the admission of light into the crystal detector.

The opportunity for misinterpretation of alpha survey results is much greater than with beta-gamma radiations. Therefore, it is advisable to obtain the services of a health physicist, who has had experience with alpha monitoring, to perform these surveys. It is essential to have an alpha check source available to be sure the instruments are functioning properly.

Alpha readings are generally expressed in counts per minute. About half of the particles are detectable by the probe, while the other half travel away from the probe. Therefore, a rough rule of thumb to obtain the number of nuclear (alpha) disintegrations per minute is to double the counts per minute detected by the instrument. The distance from the surface is an important factor due to the high absorption of alpha particles even in air. For example, a 6 mm air gap will reduce the counts about 25 percent compared to a surface contact reading, while twice that distance will cause about a 50 percent reduction.

4.1.2 *Beta-Gamma Monitoring*

Beta and gamma radiations are emitted simultaneously by many radioactive nuclides; the technique and instrumentation for beta and gamma surveys are similar. Both internal and external irradiation hazards may be presented by these materials.

Ionization chambers or GM (Geiger-Mueller) counters are the usual portable survey instruments used for beta-gamma measurements. The ionization chamber is used for higher level dose rate measurements while the GM counter is used for exposure rates below 20 mR per hour. Some GM instruments are designed also for higher level measurements. GM instruments can be saturated by high radiation levels so that false readings or even zero readings are possible in the presence of a high radiation field. Temperature extremes may cause erratic readings. A beta check source should be used to insure reliable behavior.

Discrimination between beta and gamma radiations is made by use of a shield on the probe which is thick enough to stop beta radiation. The reading with the shield in place is the gamma component; the difference between readings made with and without the shield is the beta component. Low-energy gamma radiations can be read as beta radiations at times due to significant absorption of the gamma by the beta shield.

The range of measurements by an ionization chamber varies with different makes of instruments. Some measure as low as .05 mR per hour and will range up to 1000 R per hour. Several models use logarithmic scales. It is necessary to check the battery voltage and to use a check source to test for proper function of these instruments.

Most beta-gamma instruments can be calibrated to read directly in mR per hour for a particular isotope. Some read out in counts per minute. These readings can be converted approximately to mR per hour by dividing counts per minute by 2500 (cpm/2500 $\cong$ mR/h).

A small diameter end-window detector probe, attached to a portable rate meter, is a most useful instrument for locating small radioactive (beta-gamma emitting) particles on the skin and around wound margins. It also serves in final clean-up procedures to check out areas that are difficult to decontaminate, such as around the nose, eyes, ears, and fingernails. The principal advantage of the small end-window detector is its ability to locate and pinpoint activity as compared to GM probes of 8 to 10 cm lengths.

4.1.3 *Surface Monitoring with Swipes*

A type of surface monitoring to test for transferable alpha material is to wipe the surface of interest with a clean piece of textured paper, such as filter paper. Alpha activity on the paper can then be counted in laboratory-type counters. Alternatively, portable survey instruments can be used for counting the paper, but such measurements are rough and should be used only for tentative decisions. The results will

indicate whether the contamination on the surface is readily transferable or not. This technique is widely used in surveying for low-energy beta (tritium) as well as alpha (plutonium) nuclides.

4.1.4 *Nose Swipe Samples*

The nose swipe is a special form of swipe test widely used for alpha-emitting materials. Two types of swabs have been used: a cotton applicator or a strip of filter paper about 1 by 7 cm wrapped around the end of a swab stick. A separate swab dipped into distilled water is used to sample each nostril (see Section 3.4.1). The filter paper is then dried and the exposed portion is measured in a gas-flow proportional counter. If a cotton applicator is used, the cotton fibers are teased off the applicator and spread out evenly for alpha counting. When an energetic beta or gamma emitter is being counted, such special preparations are not needed. Ideally, counting should be performed with laboratory instrumentation, such as well counters or gas-flow proportional counters. When a field alpha survey instrument is used, counting efficiency is much reduced, although a crude estimate may still be possible.

4.2 Penetrating (External) Radiation Measurements

External radiations, such as gamma rays, may be an important source of exposure in some radioactively contaminated cases. It is necessary to be alert to the possibility of mixed external and internal exposures. The circumstances of the accident alone may be a clue to this. The reading on a personnel dosimeter, such as a pocket chamber, film badge, or thermoluminescent (TLD) dosimeter, worn by the patient is likely to give the first information that indicates the extent of external exposure.

The pocket dosimeter can be either a self-reading type or a type that requires a separate reader-charger unit. These small ionization chambers, approximately the size and shape of a fountain pen, are sufficiently accurate for screening purposes. They come in a variety of ranges with full scale readings as low as 100 mR and as high as 600 R. They have a fairly uniform response to a range of energies of penetrating radiations from about 50 keV to 2 MeV. A disadvantage of this device is that physical jarring may produce a false high reading. They possess the important feature, however, that any failure or error results only in high or off-scale readings. A zero or small reading above zero

is a trustworthy value if the device was positioned properly on the person at the time of exposure.

Film badges are reliable dosimeters when properly developed and monitored with control badges. They have a range of usefulness from about 25 mR to nearly 1000 R. Careful processing, interpretation, and control procedures are required. At the exposure levels of interest for patient management, the film badge accuracy is quite satisfactory. Film badges usually contain several metallic filters over the film that enable estimation of the energy of the x- and gamma-ray exposure by comparison of the amounts of absorption in these filters. Some badges also contain film that will measure fast neutron exposure.

Thermoluminescent (TLD) dosimeters are crystals of various salts, such as LiF or CaF_2, that measure radiation by a phenomenon called thermoluminescence. Ionizing radiations displace electrons into "traps" within the crystal structure. Upon heating, these electrons are released with a simultaneous emission of light. This light, when measured by a calibrated photocell circuit, indicates the accumulated quantity of ionizing radiation. These devices have certain advantages over film in that they are not influenced by heat or humidity, and the range of dose measurement exceeds that of film. Their sensitivity, accuracy, and dependability equal or exceed that of film.

4.3 Measurements by Excretion (Bioassay) Sampling

Any radioactive material entering the body becomes, by definition, an internal emitter. It will continue to irradiate the tissues until it is either excreted by some physiological process, principally through the urine or feces, or it becomes a stable isotope through radioactive decay.

The internal emitter will be metabolized according to its chemical and physical properties. The metabolic or excretion rate at which a radionuclide leaves the body is expressed as the biological half-time, i.e., the period of time over which one-half of the radioactive isotope physically leaves the body. The principal determinants of biological half-times are the excretion rates through urine and feces. It is customary to describe the excretion rate for the various radionuclides by exponential or power function equations, which can be used to calculate the amount originally absorbed in the body and to estimate the probable cumulative whole body or organ dose up to the time of the assay as well as the probable cumulative doses at some future time.

Determining body burden values by use of excretion radioanalysis may give rise to considerable error due to differences in individual

excretion rates and day-to-day variations. A larger number of samples improves the accuracy of the estimate of the body burden, but the resulting estimate may still be off by factors of three or four. The use of one or two urine samples following a recent exposure has substantial possibility for error and should serve only as a guide to the probable exposure magnitude pending acquisition of additional data. In spite of these handicaps, excretion data still serve as a principal measurement technique for determining the presence of alpha and pure beta emitters, the internal contaminants of greatest hazard.

4.3.1 *Sample Analysis Interpretation*

Specific radionuclides can be measured easily and accurately in many radiochemical laboratories. The principal problem with excretion measurements is the inability to interpret them accurately. The desired answer is not only the amount excreted, but the quantity and distribution of the radionuclide remaining in the body. The use of excretion measurements introduces a number of serious interpretation problems that must be considered carefully each time excretion data are used. Major interpretation problems arise from lack of knowledge regarding: (1) identification of the time of the particular exposure; (2) the excretion rate of the individual for the particular nuclide; and (3) the solubility and retention characteristics of the specific fume, aerosol, dust, etc. for the contaminant under study. The possible errors that may occur in the interpretation of excretion data are discussed briefly below.

4.3.1.1. *Time of Exposure.* Radionuclides present in the body are excreted at rates that are variable with time after the exposure. The relationship of the quantity found in a urine sample to the remaining body burden is useful only if the time of exposure is known. The excretion curve is most frequently represented by the sum of several exponential equations. For soluble radionuclides, the initial excretion is highest in the first few days with a gradual decrease subsequently. Interpretations of excretion data must be made in the face of these continuously changing relationships between excretion and retention of the contaminant (Figure 4.1).

In the case of an acute single accidental exposure, the time of exposure usually can be satisfactorily established. If the individual is subject to possible chronic or recurrent exposure conditions, the question arises as to whether some of the material may represent an earlier unknown exposure(s). Where the exposure has occurred intermittently over several weeks or longer, the excretion curve will represent a complex composite of excretion rates from each exposure.

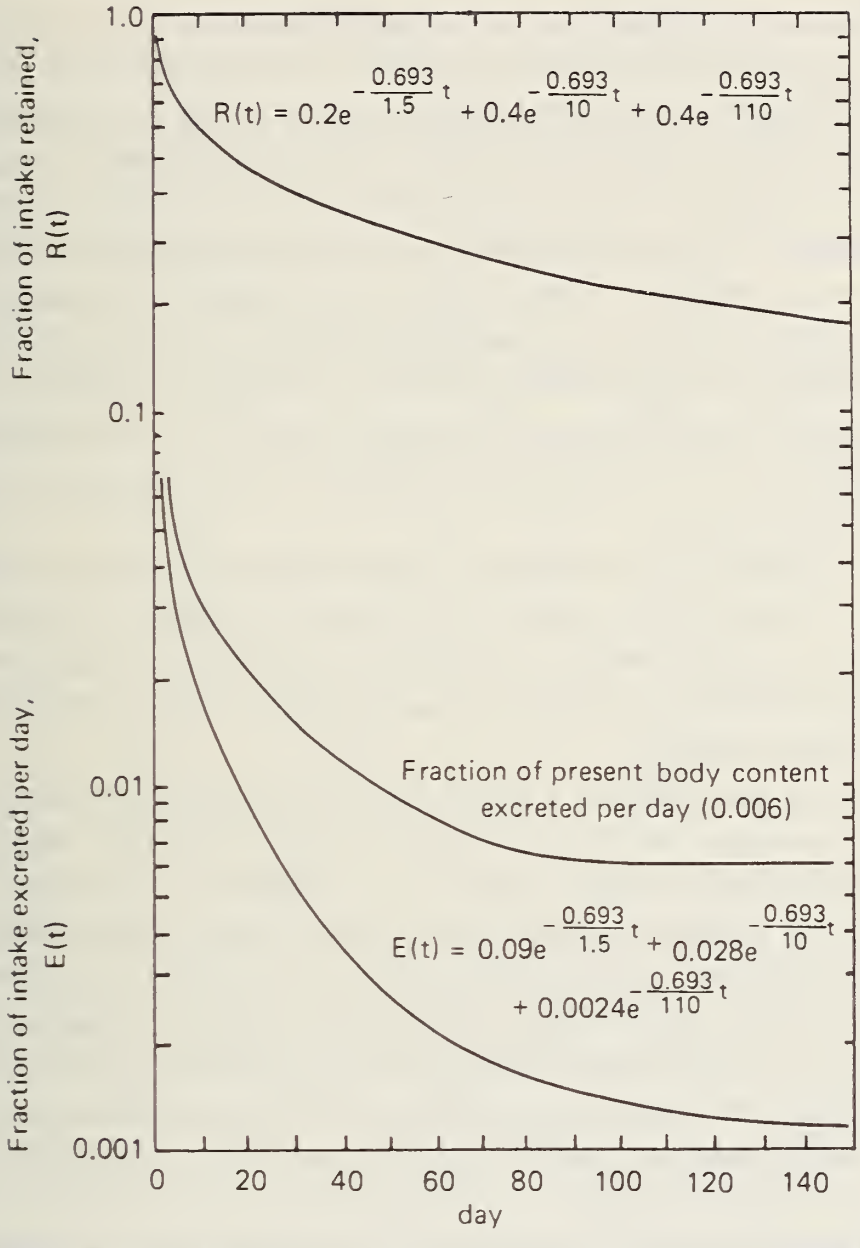

Fig. 4.1 Retention and urinary excretion of cobalt-60 following inhalation of the oxide (Freke and Duncan, 1968).

If the time of exposure is unknown, a series of measurements will provide an excretion curve that may be matched with a representative excretion curve for the particular nuclide under similar exposure conditions. The slope of the curve then permits an estimate to be made as to an approximate time of exposure. While this technique may help estimate the initial body burden, it does not help the clinician in the early management of the case since it takes a number of days to assess the results. Use of chelation or other treatment further complicates the excretion pattern and reduces the immediate usefulness of excretion analysis for estimating body burden retention. Treatment, if it is warranted, should not be deferred for the above reasons.

4.3.1.2 *Individual Variation.* Excretion rates of radioisotopes vary from individual to individual just as physiologic measurements or

clinical data vary. Therefore, excretion data must be intrepreted with the knowledge that the calculated body burden (or dose) is based on average excretion curves from which there may be considerable deviation. For example, Williams (1960) studied the biological variation in the urinary excretion of 6 patients who had received a single dose of uranyl nitrate. A better estimate of dose was calculated when more samples were collected, but even an average of multiple samples proved to have three- to four-fold variations. It is probable that measurements of other nuclides will have similar variability in individual excretion rates. The use of the first one or two samples after an acute exposure for the initial evaluation will have an even larger potential for errors.

4.3.1.3 *Aerosol Characteristics.* Excretion data, after an inhalation exposure, depend on a variety of factors bearing on the retention, clearance, and translocation of inhaled particles. Several general references (NAS/NRC, 1961, Hatch and Gross; 1964) describe the interaction of these factors.

The fate of the inhaled radioisotope is partially determined by its solubility (transportability) in body fluids. Although this is largely determined by its chemical composition, it is also dependent on physical properties of the particles, such as size, shape, and surface area. In the case of some inhaled radionuclides, the particles may consist of a matrix of various stable materials with physicochemical properties that differ from those associated with the radioisotope in question. The metabolic and physiologic behavior of this mixture may be quite different from that normally associated with the identified radionuclide.

The characteristics of aerosols to which personnel are exposed are almost always unknown and there is no precise way to reproduce and study the particular aerosol involved in an exposure after the actual event. Air samples collected on filter papers at the accident site or pieces of contaminated clothes may be used for special solubility or particle studies.

The excretion data measured after inhalation exposures will reflect the sum of the metabolic, physiologic, and physical factors involved in determining the fate of particles in the respiratory system. Urine excretion will vary depending on the uptake and circulation of the radionuclide in the blood and through the kidney. The activity in the feces represents the unabsorbed portion of the nuclides physically cleared from the nasopharynx or the tracheobronchial system, plus ingested material, and any radionuclides that may be excreted into the gastrointestinal tract. The urine/fecal excretion ratio is thus related to the mode of exposure and the solubility of the particular aerosol.

The insoluble portion remaining in the lung may not be reflected in either urine or fecal excretions. Unless the lung burden can be measured accurately by *in vivo* counting, there are no reliable means for determining the lung burden. In those instances, the measured excretion values, together with the assumed values for aerosol retention found in the standard lung models (ICRP, 1960; ICRP, 1966), can be used to estimate the unknown quantity left in the lung.

The 1966 Report of the ICRP Task Force on Lung Dynamics (ICRP, 1966), includes a schematic clearance model that presents variable clearance rates from the lung depending on different classes of solubility of compounds. While these models are useful for theoretical modeling and dose assumptions, actual clinical exposure cases may act quite differently. Each case should be studied thoroughly on its own merits and exposure estimates made for each individual.

Measurements which indicate less than the minimum detectable activity in the urine following an inhalation exposure obviously do not rule out the possibility of exposures to the lung and intestinal tract. From the practical standpoint after all but the most insoluble aerosol exposure there will probably be some detectable activity in the urine. Insoluble plutonium oxides are one important exception where excretion in urine may be negative for several weeks after exposure and then show a gradual rise as more plutonium is gradually assimilated into the systemic circulation and other organs. The use of fecal samples may contribute important information in such inhalation exposures. With both urine and fecal data, however, the interpretation of the lung exposure is fraught with uncertainty. At periods long after exposure, perhaps several years or more, the urine excretion values may reflect roughly the quantity of insoluble particulates still retained in the lung tissues or tracheobronchial lymph nodes (Voelz *et al.*, 1975) but such late estimates are useful only in radiological protection work and not for emergency management.

4.4 *In Vivo* Measurements

The summary of instrument types in Table 4.1 shows that a scintillation counter is the detector generally used for *in vivo* counting. This technique, wherever applicable, has significant advantages over bioassay methods since it does not depend on an extrapolation of individual excretion rates. The count is obtained by direct measurement of gamma activity in the body. It is influenced, however, by external contamination, which is likely to be present after any recent contaminating accident. The early measurements may be viewed as possible

maximum body burden estimates, but are likely to be false. After a few days external contamination should be reduced to a much lower level and more valid determinations can then be made.

4.4.1 *Whole-Body Counters*

These instruments detect beta and gamma radiations that are energetic enough to escape from the body. Sensitive detectors are used to assess the radioactivity in the patient. The counts are made in a heavily shielded room that provides the necessary low radiation background. Sometimes the high sensitivity of such a system may become a limiting factor after a high-level internal contamination since the count rate may exceed the counter capacity. The whole-body counters are designed to detect radioactivity at or below maximum permissible body burden levels for health protection purposes. Since they are not designed or calibrated for use in high-level accidental exposure cases, the counting systems may have to be modified by placing the detectors at a greater distance from the body or by use of absorbers around the detectors. The shadow shield whole-body counter is a special, light weight, transportable counter that incorporates the principles of the room type of whole-body counter without the need for the massive amounts of shielding. It may have a background as low as the room type counter with little variation in sensitivity due to patient size (Palmer and Roesch, 1965; Brady and Swanberg, 1965).

Whole-body counters use a variety of scintillation detectors, but by far the most common is a large, thallium-activated sodium iodide crystal. Its great advantage is its ability to discriminate between gamma rays of various energies with a good degree of resolution. Other detectors include liquid scintillators or solid plastic scintillators, either as a single detector or as multiple arrays. Most systems have the detector(s) held in a stationary position relative to the body, but some are designed for scanning motions that can show the distribution of radioactivity within the body.

The techniques for whole-body counting are described in several references (IAEA, 1964; Meneely, 1961). The "Directory of Whole-Body Radioactivity Monitors" (IAEA, 1970) lists the location and technical capabilities of the whole-body counters in the world as of 1970, including the counters available in 55 locations in the United States. All facilities and techniques listed will have more than adequate sensitivity for accident cases involving gamma-emitting radioisotopes. In most instances, the precision of measurement for gamma emitters should be within about 30 percent—a definite improvement over estimates based on excretion data.

Whole-body counters can be used to detect energetic beta emitters, such as ^{90}Sr, if special techniques are employed to count the bremsstrahlung (low-energy "braking radiations") x rays produced by such radionuclides (Olson, 1969). These determinations are less precise than for gamma emitters, but may be useful for comparison with excretion data.

Counters available in Nuclear Medicine Departments of hospitals are useful in making measurements after accidental exposures to internal emitters. The sensitivity of these counters will be adequate for most measurements, especially for higher level exposures. They should be valuable for the initial studies of the patient. Thyroid counters are also useful if a method of calibration for the particular isotope is available. The disadvantage of these impromptu measures is the difficulty in obtaining good calibrations for a particular set of measurement conditions. In general, this use should be restricted to screening techniques and should be followed by more definitive measurements at a whole-body counting facility.

4.4.2 *Chest Counters for Plutonium or Uranium*

Whole-body counting is not feasible for alpha emitters unless they also emit penetrating gamma rays. For example, plutonium-239 and -238 are alpha emitters of considerable importance that are not measurable with ordinary whole-body counters. Since inhalation is the predominant route of exposure, the measurement of plutonium in the lungs is a desirable *in vivo* technique. Currently three types of instruments are used for such measurement—proportional counters, thin sodium iodide crystals, or combined sodium iodide-cesium iodide crystals. In each case they measure low-energy x rays or gamma rays from either plutonium itself or from other contaminants associated with plutonium, such as americium-241. The energies commonly measured are the 17 keV (average energy) x rays from the plutonium decay or the 60 keV gamma ray from americium-241 decay.

Plutonium x rays are measured using a special phoswich detector which consists of a thin (3 mm) NaI crystal in front of a thick (50 mm) CsI crystal. These two detectors are combined as an anticoincidence system that can suppress the background count arising from scatter from higher-energy natural gamma rays from within the body or surrounding materials while selectively detecting the 17 keV x rays. Since absorption of such low energy radiations by the chest wall is considerable, a precise measure of chest wall thickness is required for quantitative results. This measurement is generally made with ultrasonic techniques. *In vivo* plutonium counting involves considerable

error because of the physical limitations of counting both at low count rates and at low photon energies. Minimum detectable activity over the chest is approximately 30 nCi or higher for a single ^{239}Pu count in a 30-minute period. For ^{241}Am, the minimum detectable activity is less than 0.3 nCi. Repeated counts over a period of time will increase the reliability of the data and improve detection limits. Sixteen nanocuries is considered the maximum permissible lung burden for ^{239}Pu, ^{238}Pu, and ^{241}Am. These counts must be performed within a specially shielded room as with whole-body counting. The patient must be transported to an institution that has such a facility if circumstances warrant the measurement.

A point of concern in the initial measurement of plutonium by these techniques is the inability to differentiate between traces of plutonium on the skin and a true internal lung burden. Surface plutonium suffers little or no absorption and therefore registers much more prominently than plutonium in the lungs. The shape of the 17 keV peak may permit the skilled observer to estimate whether a significant portion of the activity is on the external surface. Obviously, almost any amount of gamma emitters in or on the individual will nullify this technique since the elevated background counts will obscure the 17 keV plutonium counts. The use of Ge(Li) and intrinsic Ge detectors may aid in determining if surface contamination is present. They can also identify the presence of high-energy gamma emitters.

Detection of the ^{241}Am gamma rays is possible with NaI(T1) crystals of about 1 to 3 mm thickness. Such counters are somewhat more readily available than phoswich counters. This method also permits an indirect measurement of plutonium, if the $^{241}Am/^{239}Pu$ ratio in the particular aerosol involved in the accident is known. The technique is particularly useful for the initial evaluation after an accidental exposure. For long-term follow-up the technique leads to errors because the translocation rates and distribution of americium and plutonium within the body are different (Johnson *et al.*, 1970).

4.4.3 *Wound Monitoring Instrumentation*

The degree of difficulty encountered in measuring radioactive contamination in wounds is dependent primarily on whether the nuclides are beta-gamma emitters or alpha emitters. Survey for beta-gamma radioactivity in wounds can be performed adequately with the instruments used for surface monitoring. The major problem is likely to be the inability to locate the radioactive material within the wound so that decontamination can be carried out effectively. Use of shielding

materials with various diameters of open holes will assist in the location of high concentrations.

Sensitive scintillation probes, some as small as a 15 gauge hypodermic needle, have been developed and can be introduced into the wound to help locate the radioactivity more precisely (Finkel and Hathaway, 1956). The probes are easily sterilized by cold sterilization techniques.

Although the ability to probe the wound with a detector appears attractive, identification of the precise location of the radioactive material is seldom possible unless the contaminant is a sliver of metal or a large particle. Powders or liquids are apt to be dispersed throughout the wound.

A small end-window detector, about 1 cm in diameter, placed over the wound surface works almost as well as a special wound probe. The window usually is covered with a thin piece of plastic to prevent contamination. The sensitivity of the end-window detector is very good for survey work and the detector size is small enough to localize the contamination for effective cleansing, irrigation, or debridement.

Alpha emitters present a more difficult measurement problem in wounds. A thin film of moisture from decontamination solutions, blood, or any overlying tissue will absorb alpha radiations and effectively shield the detector. For example, plutonium deposited in a tiny scratch can easily be missed by alpha monitoring unless there is associated surface contamination in the region of the wound. Thus, wound probes that depend on detection of alpha radiations are not practical.

Some alpha-emitting isotopes have other radiation emissions that are more penetrating and useful for detection and measurement than alpha particles. For example, ^{239}Pu usually can be detected by counting the L x rays of the uranium daughter. Although these x rays (13.6, 17.0, and 20.2 keV) are rapidly attenuated by overlying tissues and self absorption in particles of the contaminant (Tyler, 1966), their penetration through 1-2 cm of tissue make them far superior to alpha measurements for wound monitoring. Special monitoring equipment is required to measure plutonium by this method.

Another technique for detecting alpha emitters depends on counting an associated radionuclide that, even though it is present as only a low precentage of the mixture, has radiation characteristics more favorable for measurement. For example, plutonium-239 nearly always contains a small percentage of americium-241 as a contaminant. The 60 keV gamma ray emitted by ^{241}Am is more penetrating and more easily measured than the 17 keV L x ray from plutonium. The half-value thickness in tissue for 17 keV x rays is about 7 mm, while at 60 keV it is about 35 mm. By determining the ^{239}Pu/^{241}Am ratio from some of the contaminant washed or cut out of the wound or from other samples

obtained from the same incident, the ^{239}Pu content can be estimated from the ^{241}Am gamma-ray measurement (Cloutier and Watson, 1967). Some scintillation detectors will not resolve such low-energy x rays. Solid-state detectors are generally better when available than scintillation detectors for this type of spectrometry. With less sensitive instruments, errors can be reduced if a thin reference source is made from the same contaminating material and a gamma spectrometer is used to examine both the wound and reference source (Jones and Saxby, 1968).

The most practical and least expensive instrument is a small thin NaI(Tl) scintillation detector, e.g., a 2.5 cm in diameter × .79 mm thick NaI(Tl) crystal, that does not have to be introduced into the wound. By using collimation to locate the activity first in the horizontal plane and then in a vertical plane, the depth of the contamination can be estimated sufficiently accurately for most debridement activities. Localization is difficult because the count rate is relatively low and collimation reduces it even further. The minimum detectable amount with such an instrument is about 0.009 nCi on the surface and 0.1 nCi at 1 cm depth. The desirable counting time is about ten minutes (Brown, 1973; Roesch and Baum, 1959). The requirements of collimation and long counting time make evaluation of plutonium contamination in a wound a slow tedious task.

One of the drawbacks of this counter is the background counting rate. However, 5 to 10 cm of lead shielding reduces the background of a thin crystal counter to about 6 percent of the unshielded value. Counting can also be done in a low background, shielded room used for whole-body counting. The major disadvantages of the thin NaI(Tl) crystal mounted on a low-noise phototube are its bulkiness and lack of maneuverability near the wound.

A more specialized wound probe has been designed that uses a 1 × 3 mm NaI(Tl) scintillation detector mounted in a 6-mm long aluminum can of 4 mm outside diameter (Fromhein *et al.*, 1976). This small wound probe, designed for medical use, has a sensitivity of 1 nCi for a ^{239}Pu point source when a counting time of 100 seconds is used.

Another recent development is the silicon avalanche detector that may replace the NaI(Tl) detectors as wound monitors for low-energy photons, such as measured for plutonium. This detector has the following advantages (Hewka *et al.*, 1970): (1) low noise and low background counting capability; (2) highest counting efficiency in the low energy region without requirements for cooling; (3) rugged and small; and (4) high signal level from the detector. A specially fabricated 3.2 mm diameter avalanche detector can detect 1 nCi of ^{238}Pu through 2 mm tissue using a 4-minute count (Modolofsky and Swinth, 1972).

Lithium-activated silicon crystals provide a spectrogram of low-energy photons having much better resolution than can be obtained from NaI(Tl) detectors. The silicon crystals are used as a surface measurement device, but they will also give an estimate of depth of the deposit by calculations of the differential absorptions of the 13, 17, and 20 keV x-ray energies of ^{239}Pu relative to depth beneath the skin.

5. Conceptual Basis for Treatment Decisions

5.1 Timeliness of Data

A major problem in the early management of persons contaminated with radionuclides is that the extent and magnitude of internal contamination is unknown. In complex contamination situations, particularly those involving alpha emitters, dosimetric evaluations may have to be delayed many days while the sequential samples of excreta or measurements of chest activity are being assessed. Conversely, treatment procedures are most effective if initiated soon after the contamination has occurred. As a result, the critical initial treatment decisions may have to be based on a knowledge of human physiology, the pharmacology and metabolism of the particular chemical compound, and whatever information regarding the exposure potential is available at the time. This judgment is best made after a detailed review of the exposure incident and with foreknowledge of the available treatment regimens and procedures that were developed in the preplanned emergency response for management of such accidents.

The earliest information after the exposure will consist perhaps of some information on the accident, probable identification of the major radioisotopes by history or early spectrometric identification, a few radiological measurements (contamination surveys, air concentrations, etc.), and no clinical symptoms or signs other than possible trauma. The probably complete absence of immediate clinical features places the physician at a great disadvantage in trying to determine the need for treatment. An initial survey for contaminating radionuclides is the first measurement required to indicate the probable magnitude of the patient's involvement in the accident. In accidents involving airborne materials, nasal swipes should be taken before the patient showers. These may serve as an index of possible inhalation exposure, although negative values do not eliminate the possibility of exposure. The physician should not delay making his initial decisions to start first aid procedures while waiting for better dose estimates. His decision will be based on rough exposure estimates, past experiences, clinical appraisal, and medical judgment. Admittedly these are vague, indeter-

minant quantities that defy definition. There may be past experience with the isotope in question that suggests that preventive and treatment procedures should be instituted immediately.

After immediate first-aid treatments, further diagnostic studies of value will be whole-body counts for gamma emitters, if available, and urine, fecal, and blood samples for radioanalysis. With these initial results it may be possible to arrive at a somewhat better estimate of the exposure. This preliminary appraisal may be adequate to suggest additional treatment methods, such as chelating agents if they have not already been employed.

After initial treatment measures, a time interval is generally available for obtaining detailed physical assessments of external and internal contamination before embarking on additional therapeutic procedures. Advance emergency planning will reduce the time required for dosimetric evaluation because the plan should list available sources for appropriate calibration sources, spectrometric measurement instrumentation, and dosimetry and analytical chemistry services. This is also the time when medical and health physics consultants familiar with management of radiological accidents can be brought in for consultation and advice.

5.2 Risk/Benefit Considerations

After the initial treatment decision, more accurate assessment of the initial burden can be made by repeated physical and bioassay measurements over a period of time. These improved estimates should provide a rational basis for determining the extent of further treatment.

The estimated cumulative radiation dose to the critical organ will help in evaluating the need for treatment, particularly if the therapy involves risks. The physician is responsible for estimating "probable" risk to the patient from both the exposure and the therapeutic procedures. The risk estimate is a professional judgment of the statistical probability of radiation-induced disease occurring within the patient's lifetime, a judgment that warrants the assistance of expert consultants. Evaluation of the seriousness of the exposure in some instances may be assisted by considering the maximum permissible body burden (MPBB) of the isotope listed for occupational exposure control purposes (NCRP, 1959; ICRP, 1960). The MPBB value is set so that an occupational exposure for the working life of an individual at that maximum permissible value "is not expected to entail appreciable risk of damage to the individual or to present a hazard more severe than

those commonly accepted in other present day industries" (ICRP, 1960).

The MPBB is not very useful in judging exposure risks from accidental, short-term exposures because it is based on lifetime continuous exposures. The risk from acute exposures should be evaluated on the basis of the estimated radiation doses and dose rates to various organs. These doses cannot be measured, but can be calculated using information on the quantity of radionuclide in the body or specific organs, typical metabolism and distribution patterns, and the radiological properties of the radionuclide. In Section 2, Table 2.6, an approximate dose to a selected critical organ is given for one microcurie of the radionuclide in the organ.

The seriousness of radiation exposure may be judged against basic radiation protection criteria (NCRP, 1971). For accidental exposures this NCRP report, on page 102, states "Since planned whole-body doses up to 25 rems are reasonably accepted for emergency conditions, it follows that accidental doses up to the same magnitude should not cause major concern. At higher levels, and especially where the whole-body dose reaches 100 rems, medical observation and subsequent actions based primarily on medical opinion are the important aspects." Although this guidance is intended primarily for external radiation exposure to the whole body, it is equally applicable to individual organ doses from short-lived internal emitters.

The physicochemical form of the contaminating material, or the particulate matrix in which it is located, may cause a distribution of the radionuclide within the body that is different from that assumed for purposes of calculating the maximum permissible exposure limit. Therefore, the hazard of a particular contaminant may be greater or less than that assumed in the development of the MPBB guides. These variations, however, are probably no greater than some of the other approximations that will be needed for arriving at the dose evaluation used for treatment decisions.

The bases for treating the contaminated patient are common to all medical practice. The physician must judge the ultimate benefit versus the potential harm of the procedures he performs. This decision becomes more difficult when the potential hazard is a long delayed health impairment, the possible occurrence of which can be estimated only by applying the probabilities of developing subsequent biologic effects based on radiological measurements. Weighed against this hazard is the possibility of immediate or short-term, as well as long-term, health risks from the treatment. The judgment of the physician can lead to a range of action: no treatment, debridement of contaminated tissues, non-specific supportive treatment, or a variety of medi-

cations, including repeated internal chemotherapy for several years. In one dramatic instance, the decision resulted in attempts to restore a young worker's radioactively contaminated hand that had been accidentally amputated (Brodsky, *et al.* 1972). Generally, the physician will possess a better intuitive judgment as to the risks of treatment than on the health risks accompanying the internal deposition of radionuclides. The following brief discussion and Tables 5.1 to 5.3

TABLE 5.1—*Parameters of inhaled plutonium risk model*

Organ	Latent period	Period over which risk occurs	Risk coefficient
	(years)	(years)	(cancers per year per rem)
Lung	15	30	1.3×10^{-6}[a]
Bone	10	30	0.2×10^{-6}[a]
Liver	15	30	0.08×10^{-6}[b]

[a] Risk coefficients from the BEIR Report (NAS/NRC, 1972).

[b] Risk coefficient for liver from the LMFBR Environmental Statement (USAEC, 1974).

TABLE 5.2a—*Probability of survival after inhalation of insoluble PuO_2 (Class Y)*[a]

Exposure age	Amount inhaled[b]	Probability of survival to age				
		40	50	60	70	80
(years)	(nCi)					
20	0	0.963	0.917	0.821	0.640	0.364
	1000	0.961	0.911	0.812	0.631	0.358
	10000	0.946	0.863	0.737	0.555	0.312
	100000	0.798	0.493	0.275	0.150	0.076
40	0			0.852	0.664	0.378
	1000			0.851	0.660	0.373
	10000			0.836	0.624	0.338
	100000			0.704	0.354	0.122
60	0				0.780	0.443
	1000				0.780	0.442
	10000				0.780	0.434
	100000				0.780	0.362

[a] Class Y is a pulmonary clearance classification of inorganic compounds that are retained in the lung and clear slowly over a period of years (ICRP, 1966).

[b] The model uses the retentions in the lung and the whole body shown in Table 5.2b. nCi is the symbol for nanocurie.

TABLE 5.2b—*Predicted lung and body burdens after inhalation of insoluble PuO_2*

Inhaled	Initial lung burden	Immediate body burden	Eventual body burden
(nCi)	(nCi)	(nCi)	(nCi)
1000	150	4	50
10000	1500	40	500
100000	15000	400	5000

TABLE 5.3—*Probability of having cancer*[a] *by given age after inhalation of insoluble* PuO_2 *(Class Y)*[b]

Exposure age	Amount inhaled	Probability of cancer[a] by age				
		40	50	60	70	80
(years)	(nCi)					
20	0	0.005	0.014	0.035	0.078	0.150
	1000	0.007	0.020	0.044	0.090	0.165
	10000	0.023	0.070	0.126	0.193	0.257
	100000	0.171	0.450	0.637	0.725	0.754
40	0			0.031	0.076	0.154
	1000			0.032	0.081	0.161
	10000			0.047	0.122	0.216
	100000			0.182	0.437	0.579
60	0				0.053	0.145
	1000				0.053	0.146
	10000				0.053	0.155
	100000				0.053	0.236

[a] The model includes all cancers in the non-exposed individual according to 1970 United States statistics and adds the increased risk of developing lung, liver, or bone cancers in individuals after inhalation of plutonium.

[b] Class Y is a pulmonary clearance classification of inorganic compounds that are retained in the lung and cleared slowly over a period of years (ICRP, 1966).

illustrated possible risks from internal deposition of a long-lived radionuclide, plutonium-239.

Some rough estimate of the risk from radioactive materials may be made from the currently available risk models, the best known and most widely used of which are in the BEIR Report (NAS/NRC, 1972). These models use a linear, no-threshold extrapolation from high doses and high dose rates to the lower doses and dose rates frequently encountered in intakes of radioactive materials. There is no scientific proof that such a model is appropriate and it may well overestimate the risks.

The BEIR models prescribe a latent period before cancer develops, a plateau period which indicates the time over which the radiation is effective in producing cancer, and a risk coefficient that expresses the number of cancers per unit dose. The BEIR Report actually provides four models: an absolute risk model in which the risk during the plateau period is a constant per unit of dose; a relative risk model in which the risk during the plateau period is a fraction of the normally occurring cancer risk; and two plateau periods for each, a limited plateau and a remainder-of-life plateau.

In the following, the risks to the individual are estimated after inhalation of known quantities of plutonium by use of the absolute risk model and limited plateau period to illustrate the risks from one radionuclide at various levels of exposure. The parameters of the model are given in Table 5.1.

In estimating the risk it is necessary to include the competing risks that an exposed person faces. For example, an individual killed in an accident or from another disease will not get cancer. The results must be expressed in probabilistic terms. As a measure of the risks to be encountered at various ages the data from the 1970 U.S. census was used as a cohort for the individuals at each given age. The added risk from plutonium was calculated for each age group and combined with the normal risk to provide a new estimate. Two quantities were calculated: (1) the probability of the individual living to a given age, with and without exposure; and (2) the probability of the individual having cancer by a given age, with and without exposure. These results are given in Tables 5.2 and 5.3.

These results are very rough because of the assumptions of risk coefficients and the flat time-response curve. They are not presented for use in individual exposure cases, but rather they are illustrative of factors influencing future risk. They show the importance of the age of the individual at time of exposure and the rapid change in overall risk as the amount inhaled rises from 10,000 to 100,000 nanocuries. The bulk of the assigned risk is due to lung cancer rather than bone or liver cancer so that modes of intake other than inhalation will result in lower risk.

5.3 Soluble Versus Insoluble Compounds

The solubility (transportability) of a compound or mixture containing radionuclides determines its distribution in the body and hence the appropriate treatment regimen. No material is absolutely insoluble and even very refractory materials, for example, high-fired plutonium oxide or thorium oxide, frequently contain a small soluble fraction or may consist of such small particulates as to behave like a soluble material that rapidly leaves the lung or a wound. Therefore, when it is stated that the material involved in an incident is "insoluble," some fraction of it may translocate rapidly from the site of an internal deposit and possibly be more accessible to treatment than expected. Conversely, some materials reported as highly soluble may contain a relatively insoluble fraction.

Many metals, even as the usually soluble nitrate salts, upon contact in the tissue fluids at pH 7.2 – 7.4 are rapidly converted to the less soluble hydroxides or are complexed so that a portion remains at the site of entry over relatively long periods. In instances where the radioactivity is induced by neutrons from reactors or accelerators, radionuclides usually considered as soluble, such as ^{65}Zn and ^{60}Co, may

be produced within an insoluble matrix material and behave as relatively insoluble material. Heavy metals, especially the actinides and lanthanides, behave in the body as if there is both a soluble (transportable) fraction and a comparatively insoluble (nontransportable) fraction, the former moving rapidly via the blood and the latter being retained in the reticuloendothelial or lymphatic systems or bound at the exposure site. That portion behaving essentially as ionic, soluble, or monomeric (various terms are used since often the exact nature is unknown) is usually translocated soon after exposure and is generally more susceptible to removal, particularly by chelating agents. The less mobile portion may be susceptible to physical methods of removal and is usually less amenable to other types of treatment. Deposits of less transportable material may slowly release the radionuclide into the lymphatic or systemic circulation. Schofield (1969) noted such vagaries in treating 3 cases of plutonium contaminated wounds.

In spite of the above qualifications, information on solubility is useful as an indicator of the need to begin certain treatments, especially chelation therapy. Samples of the offending agent can be tested in the laboratory for biological solubility and thus the metabolism and mobility of the incorporated radionuclide and effectiveness of treatment can be estimated. Experience has shown, however, that a therapeutic clinical trial is the most reliable test, if the probable exposure to the radionuclide warrants that treatment. Treatment should be given immediately in order to secure maximum benefit in those situations where treatment risk is judged to be small compared to the exposure risk even though the solubility factor is still unknown. Further treatments would then depend on the results of continued evaluation.

It is difficult to state general rules on solubility *in vivo*. Anionic forms, such as pertechnetate, move rapidly from the deposition site, and uranyl, ruthenyl, and neptunyl ions are absorbed more readily and have a distribution pattern different from element valence states more likely to form stronger hydroxides, for example Pm(III) or Pu(IV). Transuranic trivalent metals, even as oxides, are more soluble than the tetravalent metal oxides. Some particulate forms of the same radionuclide may exhibit different solubility characteristics due possibly to autoradiolytic-induced ablation, surface area considerations, and more intense radiolytic-induced changes in the local environment. Most of these phenomena are a function of radiation intensity and thus related to specific activity. Inhaled $^{238}PuO_2$ in animal experiments, and also in an *in vitro* test system, was considerably more soluble than similarly prepared $^{239}PuO_2$ (Stuart *et al.*, 1968; Park *et al.*, 1969; Park *et al.*, 1972). The specific activity of ^{238}Pu, about 270 times that of ^{239}Pu, may account for this difference.

When radiometals are bound to organic agents, either as complexes

or in covalently bonded compounds, biological solubility usually is distinctly altered. Except for that portion of radiometal released by degradation or exchange, distribution will usually be more akin to that of the organic moiety. Solubility of the metal, once released from its carrier, will likely be that of the monomeric metal. Metals such as Ca, Zn, and Na are generally quite mobile, but the metabolism of these elements, including their radioisotopes, is influenced by availability and metabolic need of the particular element. When several radiometals are involved in an exposure, each generally behaves independently of the others as far as solubility is concerned. One exception is that trace metals inhaled in insoluble particles will be released from the particles at rates determined by the bulk chemical matrix of the particle. In some cases this behavior might dictate the order of treatments to be given. Radioactive inert gases, such as krypton or argon, generally act as gases with limited absorption in the body when inhaled. Radon, also a gas, is a daughter product of radium and is frequently absorbed on particles in the air.

5.4 Multiple Isotope Effects

Many radionuclide exposures, especially around reactors or in nuclear industries, involve more than one isotope; the minimum is one radionuclide and a stable decay product. One group of radionuclides that is widely available in a large segment of the nuclear industry has its own abbreviation, MFP (mixed fission products). Activation products, such as ^{54}Mn or ^{60}Co, may also be present. Others likely to be encountered in combinations are thorium, uranium, and radium together with their decay products. Plutonium with ingrown americium, curium, and neptunium is another group. Although there is little experimental basis on which to suggest treatment, it is usually possible to identify the one or two radionuclides that present the principal hazard. In the case of a significant exposure to MFP, treatment would depend on the age of the material after irradiation in the reactor. At about 1 day after removal, radioiodines would make a significant contribution to the hazard; at later times, ^{144}Ce-^{144}Pr, ^{137}Cs, $^{89-90}$Sr, ^{106}Ru-^{106}Rh, and ^{95}Zr-^{95}Nb would be the principal radionuclides (Glasstone, 1955; BRH, 1960). The predominant radionuclides must be identified before the proper treatment regimen is selected. In case of depositions of radionuclides having atomic numbers higher than uranium, element 92, the choice of treatment is much simpler since currently one chelating agent (DTPA) may be used for all.

6. Resumé of Experience With Important Radionuclides

6.1 Americium

Americium, (Am), element number 95, is a member of the group of transuranic elements, and has isotopes of mass 237 to 246. It does not occur in nature. The two most important isotopes are americium-241 and americium-243. Americium-241 is a daughter product of plutonium-241 and therefore it is associated frequently with plutonium processing or handling. Americium-243 is produced from uranium-238 or plutonium-239 by multiple neutron capture.

Americium-241 has a physical half-life of 458 years and an effective half-life in bone of about 140 years. The assumed effective half-life in the whole body is 100 years and in liver 40 years (ICRP, 1972). Americium-241 decays by emitting alpha particles of 2 distinct energies [5.49 MeV (85 percent) and 5.44 MeV (13 percent)] to form neptunium-237. The principal photons emitted by ^{241}Am are gamma rays of 60 (36 percent) and 26 keV, and conversion L x rays of neptunium with energies centered at about 18 keV.

Americium-243 has a physical half-life of 7950 years and assumed effective half-life in bone of 195 years, in whole body of 100 years, and in liver of 40 years. Americium-243 decays by emitting alpha particles of 2 energies [5.28 MeV (87 percent) and 5.23 MeV (11 percent)], and two soft gamma rays (44 and 75 keV).

Americium exhibits all oxidation states from II to VII, but the trivalent state is the most common. The metal oxidizes slowly in air and dissolves readily in dilute HCl.

Reactor-grade plutonium contains a few percent of americium-241, depending on the age of the material and its radiation history in the reactor. Americium-241 is used as a radiation source for static eliminators, smoke detectors, thickness gauges, and calibration sources. Combined with beryllium, americium is used as a neutron source. It is also used as target material for producing ^{242}Cm in accelerators.

Depositions of americium in the body occur primarily by inhalation of particulates or through skin wounds. Absorption through the gas-

trointestinal tract is only about 0.03 percent in adult animals, although it is probably higher in newborns and the very young (Durbin, 1973). Absorption through intact skin is thought to be very small, but probably, as is the case with plutonium, is increased when it is dissolved in solutions having an acidity that destroys the integrity of the skin barrier. Skin absorption of various solutions of plutonium in man and animals has been observed to range from 0.002 to 0.25 percent for exposures of up to one day duration (Vaughan *et al.*, 1973). Similar studies have not been reported for americium.

Absorption through wounds will depend on the chemical form and volume of the material and probably the nature of the wound. Intramuscular injections of americium in rats resulted in the following absorption (redistribution) from the injection site in the first day: $^{241}Am\ (NO_3)_3$—10 percent, $^{241}Am_2\ (SO_4)_3$—24 percent, and $^{241}AmCl_3$—58 percent. Rapid uptake continued to occur during the first few days (Durbin, 1973).

Inhalation of particles is an important internal exposure route in industry. Uptake depends markedly on the chemical and physical properties of the particulates (see Section 3.2). Studies in rats indicate 75 to 85 percent of the initial lung burden of americium compounds is absorbed into the body, about 10 percent is retained in the lung, and less than 15 percent is cleared from the lung and excreted in the feces. These percentages do not include the 50 to 90 percent of inhaled material that is promptly cleared from the lung (Durbin, 1973) and eliminated via the gastrointestinal tract.

Once absorbed, americium is deposited primarily in liver and skeleton with lesser amounts initially present in kidney and spleen. In most animal studies, 80 and 90 percent of parenterally administered ^{241}Am is partitioned initially with 20 to 35 percent in the skeleton and 50 to 70 percent in the liver. In rats, after deposition of ^{241}Am in the respiratory system and absorption into the circulation, approximately 35 percent was transported to the liver and 57 percent to the remaining carcass (Crawley and Goddard, 1976). The total activity transported to extrapulmonary tissue was greater after its administration as the citrate than as the nitrate. The skeleton is the probable critical organ for long-term effects due to the longer effective half-life in bone compared to other organs. The liver is also an organ of concern.

The pathology of ^{241}Am exposure by intraperitoneal injection in mice has been described (Nilsson and Broomé-Karlsson, 1976). Very high doses of 16 and 18 μCi/kg seriously damaged the hematopoietic tissues, bone tissue, and testes. The highest frequency of induced tumors, 27 percent in the skeleton and 10 percent in hematopoietic

tissue, was in the 8 μCi/kg dose range. Liver tumors were not increased significantly in any group. Degenerative lesions of the liver, adrenal glands, kidney, and heart were found mainly in the higher dose groups.

Metabolism and dosimetry studies of inhaled ^{241}Am oxide in beagles (4.4 to 4.9 μCi/kg) showed that the greatest long-term doses are received by the tracheobronchial lymph nodes, liver, lung, bone, and thyroid in descending order (Thomas *et al.*, 1972). The total white cells, platelets, lymphocytes, and neutrophils of the blood were reduced, in number. Pathologic findings centered around fibrotic changes in lung and lymph nodes, fatty deposits, and cellular degeneration in liver, bone marrow depletion, glomerulosclerosis, and severely damaged thyroid. These dose levels, about 8,000 times the maximum permissible body burdens for workers, for time periods of 127 to 1022 days, do not necessarily indicate where long-term pathology, such as carcinogenesis, may develop.

In man, the mode of exposure determines the distribution in the body. In six persons chronically exposed to an unknown chemical form of americium by inhalation over a period of six years, most of the activity was in the skeleton with little activity in the soft tissues, except for the liver (Wrenn *et al.*, 1972). The ratios of activity found in the liver relative to the skeleton for a male adult and a 10-year old child were 0.1 and 0.3, respectively. In another instance, two men were studied for a period of nearly 4 years after accidental inhalation of americium oxide (Fry, 1976). At day 324, an estimated 41 percent was in lung, 47 percent in liver, and 12 percent in bone; at day 1392 the percentages were 18 in lung, 47 in liver, and 35 in bone. The long-term transfer from lung to blood, considered to be relatively small by the Task Group on Lung Dynamics (ICRP, 1966; 1972), appears to be a more important factor in lung clearance than ciliary mechanisms. It has been proposed (ICRP, 1972) that, for all americium compounds, the distribution be considered 45 percent in bone, 45 percent in liver, and 10 percent in other tissues or excreta.

Treatment for internal deposition of americium, regardless of the route of exposure, is the immediate administration of DTPA (see Section 7.3.5.3). If this agent is not immediately available, the use of EDTA (Section 7.3.5.2) can be substituted although it is less effective. In the event of a contaminated puncture wound, the local area should be excised promptly since the absorption rate of americium can be rapid (over 50 percent in the first day). CaDTPA (or CaEDTA) should be administered prior to surgical excision if possible. The effectiveness of DTPA has been documented by a number of investigators (Nenot *et al.*, 1972; Volf and Seidel, 1974; Lloyd *et al.*, 1975a; 1975b; Seidel, 1975; 1976; Cohen *et al.*, 1976). Dogs given ^{241}Am citrate intravenously

(0.3 μCi/kg) and treated 2 weeks later with daily subcutaneous injections of ZnDTPA had a liver content of ^{241}Am that was reduced after 203 days of treatment by a factor of 200 and a nonliver content reduced by a factor of 3, on the average, compared to untreated controls. After 387 days of treatment the nonliver content of ^{241}Am was about a factor of 10 less than in the untreated animals. The daily dose of ZnDTPA was equivalent to approximately 1 g DTPA daily in a 70-kg man (Lloyd *et al.*, 1975a). Daily injections of ZnDTPA also hastened the disappearance of ^{241}Am from a simulated wound site, prevented almost completely the translocation from the depot to the liver and skeleton, and reduced significantly the total body ^{241}Am content through increased excretion (Lloyd *et al.*, 1975b). Nenot *et al.* (1972) started treatment of rats 21 days after exposure to ^{241}Am nitrate by aerosol. CaDTPA, given twice a week intramuscularly (50 mg/kg body weight), had reduced the ^{241}Am content in the bone by a factor of 5.3 by day 100.

Seidel (1975, 1976) showed with rats that treatment of ^{241}Am exposure with DTPA is less effective if begun on day 4 than if started immediately after exposure. CaDTPA was clearly superior to ZnDTPA for the first dose given a few hours, or at most, one to two days after exposure, but otherwise ZnDTPA and CaDTPA were equally effective in enhancing the elimination of ^{241}Am.

Brodsky *et al.* (1968) treated a glovebox operator who had inhaled dust containing a mixture of ^{241}Am and ^{239}Pu oxides after a dry box explosion. One gram per day of CaDTPA given intravenously on days 5 through 8 increased the excretion of ^{241}Am in the urine to 50–100 times preinfusion levels. This marked increase indicates that CaDTPA can be effective even though the americium is in an oxide form, which was considered previously to be only slowly soluble in the lung.

Reasonable effectiveness of chelation therapy has been demonstrated in man even if started months or years after exposure to ^{241}Am. Fasiska *et al.* (1971) treated a person with a body burden of 1.8 μCi ^{241}Am from exposures to oxides of americium that took place over a period of several years (see also Brodsky *et al.*, 1969). Chelation therapy, 1 g DTPA weekly over 30 months, removed about half the total body burden, mainly from liver and lung, but the bone component, about 1 μCi, was relatively unaffected. Continuation of DTPA administration at 0.5 g/week appeared to have less effectiveness compared to the earlier regimen. No adverse side effects were observed in this long-term, low dose DTPA therapy (Slobodien *et al.*, 1973).

Cohen *et al.* (1976) have shown in both man and baboon that DTPA reduces the soft tissue and skeletal deposits of ^{241}Am much more effectively in the juvenile than in the adult. In baboons, the ^{241}Am

removed from the skeleton by DTPA is excreted primarily in urine, while increased ^{241}Am in the feces is from the liver.

The therapeutic effectiveness of chelation therapy was demonstrated in the case of a chemical operator, heavily contaminated with americium on his skin, including nitric acid burns, and contaminated wounds about the face and neck from flying debris (Heid *et al.*, 1979). Decontamination efforts on intact skin, wounds, and burns were extensive. During the first 935 days after the accident, a total of 548 g of ZnDTPA and 20 g of CaDTPA were administered intravenously. The dosages ranged from 1 g CaDTPA every 8 hours for several days in the first week after exposure to 1 g ZnDTPA daily until eleven months after exposure; then the drug was reduced to 3 times per week. No complications have been noted from this extensive course of therapy. It is estimated that the liver burden of ^{241}Am was reduced from 380 μCi to less than 0.2 μCi, and the bone burden from 380 μCi, estimated, to 25 μCi. Thus, the therapy is estimated to have been over 99 percent effective on the liver burden and over 90 percent effective on the bone burden. A total of 1100 μCi was excreted in urine and feces during the first 2 years following the accident.

6.2 Californium

Californium (Cf), element number 98, is a member of the actinide series. While there are thirteen isotopes with mass numbers from 242 to 254, the isotope ^{252}Cf is the most likely to be encountered and its most common valence is 3+. Californium-252, half-life 2.6 years, decays by emitting a 6.12 MeV alpha particle in 97 percent of decays, accompanied by gamma rays of 43, 100, or 160 keV. The property that makes ^{252}Cf especially interesting and useful is that it undergoes spontaneous fission with emission of 3.8 fast neutrons per fission; its fission half-life is 85.5 years.

Californium-252 is used primarily as a neutron source. One of the more attractive medical uses employs the neutron emission in the treatment of cancer. It is encapsulated and sealed in stainless steel and platinum and used in place of radium for interstitial or intracavitary applications (Seaborg, 1973; Wright, 1968). In industry, californium sources are used for neutron diffraction measurements, neutron radiography, neutron activation analyses, and as a neutron excitation source in nuclear reactors. It is also found in thickness gauges that use the alpha particle for measuring gas pressures and the thickness of very thin films. In geological prospecting, small ^{252}Cf sources are used in detecting gold, silver, and water in the soil.

Californium-252 presents serious external and internal radiological hazards. Inhalation and wounds are the most significant routes for accidental internal exposure. Absorption from the intestinal tract is negligible (Denham, 1969). Absorption of inhaled Cf compounds from the lung has not been studied experimentally, but Cf will probably be transported to the systemic circulation like other actinides, e.g., americium or curium. Uptake into the pulmonary lymph nodes is also of concern (Denham, 1969). Californium-252 in the systemic circulation is deposited rapidly in bone. In adult rats, over 60 percent of an intravenous or intramuscular injection of a citrate complex has been deposited in the skeleton within four days. In all species studied thus far, initial skeletal deposition of californium has been greater than that of americium or curium (Durbin, 1973). About 14 percent of the injected dose in rats was deposited initially in the liver, but by 90 days over 90 percent of the liver content was excreted via the bile into the intestine (Durbin *et al.*, 1973). Whole body retention, mainly in bone, lasts at least 11 years in the beagle; ^{252}Cf deposited in humans is estimated to have a biological half-time of about 175 years and an effective half-life of 2.2 years. The maximum permissible body burden is 0.01 μCi (0.000019 μg) and a permissible lung burden proposed to the ICRP is 0.004 μCi (Dolphin, 1973).

The excretion of californium in the urine (alpha counting) is used as a method of monitoring workers for possible internal exposures and is the principal measurement to use after accidents. *In vivo* counting is difficult to interpret because of the complex spectrum of gamma rays produced during fission. By use of special sensitive counters, 0.0003 to 0.005 μCi can be detected (Newton and Eagle, 1972).

There have been few reported ^{252}Cf exposures to humans. After inhalation of $^{252}Cf_2O_3$ particles by two workers, urinary clearance rate half-times of 10 to 12 days were observed after an initial clearance half-time of about one day (Poda and Hall, 1975). Treatment consisting of early aerosol DTPA chelation and saline catharsis was thought to have decreased deposition and enhanced clearance of the californium. Due to the paucity of human treatment data, the suggested therapy is based on animal experimentation.

Internal deposition of Cf as a result of an inhalation exposure or contaminated wounds should be treated immediately with CaDTPA (Section 7.3.5.3). Since ^{252}Cf, like other trivalent actinides, is transported rapidly from contaminated wounds into the systemic circulation (Morin *et al.*, 1974) and deposited in the skeleton, prompt treatment with CaDTPA is especially important (Durbin, 1973; Parker *et al.*, 1962). Wounds should be treated as described for plutonium in Section 7.2. Once bone deposition occurs, there is little prospect of removing

appreciable amounts with chelation therapy, although treatment started some days after exposure may help remove transuranics deposited in the liver, lung, and other soft tissues (Brodsky *et al.*, 1969; Fasiska *et al.*, 1971). DTPA treatment was still somewhat effective when started three weeks after ^{252}Cf injection (Morin *et al.*, 1974).

6.3 Cerium

The principal radioactive isotopes of cerium, element number 58, that are likely to be encountered are ^{144}Ce and ^{141}Ce. Cerium-144 is a fission product of uranium that emits beta rays (0.19, 0.24, and 0.32 MeV) and gamma rays (seven energies ranging from 0.034 to 0.133 MeV). Its physical half-life is 284 days. Cerium-141 is formed by exposing stable ^{140}Ce to neutron bombardment; it emits beta rays (0.44 and 0.58 MeV) and one 0.145 MeV gamma ray. The physical half-life of ^{141}Ce is 32 days. The physical, chemical, and biological properties of radiocerium have been compiled and evaluated recently by the NCRP in Report No. 60 (NCRP, 1978).

In the work place, radioactive cerium isotopes are most likely to be encountered as a component in mixed fission products. Exposure could occur around experiments in test reactors or at fuel reprocessing plants. Cerium in more purified forms may be used experimentally in chemical or biological laboratories. Its limited use as a separated isotope may account for the paucity of reports on cerium exposure in humans. Sill *et al.* (1969) described an exposure at a reactor facility where a mixture of cerium isotopes (36 μCi, ^{141}Ce; 27 μCi, ^{144}Ce) and zirconium (13.5 μCi, ^{95}Zr-^{95}Nb) was inhaled. A dose of about 10 rem was judged to have been given to the lower large intestine since practically all material was eliminated from the lung and gastrointestinal tract during the first four days. No activity was detected in the urine. Rundo (1965) followed the retention of radiocerium after an accidental inhalation of irradiated uranium particles. Six days after the accident, the subject's body burden was estimated to be 16.5 nCi of ^{141}Ce and 29 nCi of ^{144}Ce. The longer-lived ^{144}Ce appeared to have an effective half-life of about 280 days, nearly the same as the physical half-life.

Radiocerium is poorly absorbed from the intestinal tract in man and many species of animals. In mature rats the absorption of oral doses of radiocerium is less than 0.05 percent (Hamilton, 1947; Durbin *et al.*, 1956; Moskalev, 1959). Higher rates of absorption have been measured in young animals, such as weanling mice. Absorption of radioactive $CeCl_3$ from nasal membranes in Syrian hamsters was less than 4

percent (Cuddihy and Ozog, 1973). Studies in monkeys of the absorption of $CeCl_3$ after inhalation indicated that systemic absorption was always below 10 percent of the initial lung burden (Ducousso and Pasquier, 1974). The liver is the critical organ for the shorter-lived isotopes of cerium, whereas the bone is the critical organ for cerium-144, the radioisotope with the longest physical half-life (284 days). For material ingested or inhaled but not transported by the systemic circulation, the critical organs are the lower large intestine and the lung, respectively.

Treatment of radiocerium exposures should be started promptly by the use of CaDTPA or ZnDTPA (Section 7.3.5.3). Tombropoulos *et al.* (1969) were able to reduce the body burden in dogs after inhalation of $^{144}CeO_2$ by 90 percent within 30 days by use of CaDTPA compared to the 30 percent reduction in untreated controls. Treatment by aerosol or intramuscular injection (42-55 mg/kg body weight) was about equally effective. Effective DTPA therapy for a ^{144}Ce inhalation exposure in man was demonstrated by Glenn *et al.* (1979). The effectiveness of treatment depends markedly upon the promptness with which it is begun and the solubility of the cerium compound in the lungs. In mice, intraperitoneal injections of DTPA proved to be life saving in all animals given a lethal dose of 14.6 μCi/g, of $^{144}CeCl_3$ by intraperitoneal injection (Il'in *et al.*, 1964).

6.4 Cesium

Cesium, (Cs), element number 55, is an alkali metal that has twenty-one radioactive isotopes. The two with the longest physical half-lives, ^{137}Cs (30 years) and ^{134}Cs (2.1 years), are the most likely to present contamination problems. Cesium-137 decays by emitting beta particles of two different energies, 0.51 MeV (95 percent) and 1.17 MeV (5 percent), and is accompanied by a 0.662 MeV gamma ray from its daughter product. Cesium-134 decays by emitting beta rays with six different energies ranging from 0.09 to 1.45 MeV [most abundant is 0.65 MeV (68.4 percent)] and gamma rays with seven different energies ranging from 0.48 to 1.37 MeV.

Cesium-137 is by far the more likely to be encountered because it is an important fission fragment produced during fissioning of either uranium or plutonium fuels. It has been the subject of many radiobiological and metabolic effects studies because it is one of the long-lived fission products found in the environment and in man as a result of worldwide fallout associated with atmospheric weapons tests. It is

used in industry as a sealed gamma source in thickness gauges, and in medicine and research as a sealed source for therapy and as a tracer substance.

Cesium and potassium have similar chemical and biochemical behavior, including distribution and metabolism in the body. Cesium is soluble in body fluids, is distributed more or less uniformly throughout the body, and is rapidly eliminated by the kidneys. After ingestion, ^{137}Cs is absorbed rapidly and completely with about 10 percent being excreted within the first 2 days. The subsequent biological half-time, based on studies of contaminated cases occurring in industry or research laboratories, averages 109 days with a range from 68 to 165 days. These values are similar to those found on volunteer subjects after intravenous or oral intakes (Cohn *et al.*, 1963; Richmond *et al.*, 1962; Rosoff *et al.*, 1963; Van Dilla, 1965). The biological half-time is much shorter in children, ranging from 12 days in infants to 57 days in older children (Weng and Beckner, 1973; Lloyd, 1973); it is also shorter in women (84 ± 27 days) than in men (Lloyd *et al.*, 1966).

During the early 1960's, at least 19 human exposures to ^{137}Cs were reported in the literature (Hesp, 1964; Jeanmarie, 1964; Jordan *et al.*, 1964; Melandri and Rimondi, 1964; Miller, 1964; Taylor *et al.*, 1962). There were both inhalation and ingestion exposures, but most were of the order of 1 μCi or less; only one case exceeded the maximum permissible body burden of 30 μCi. These cases were not serious exposures and were followed primarily to study the metabolism and turnover rate of cesium and they were untreated. The number of reports of contaminated cases since 1965 has decreased, a trend that may indicate either better radiological protection procedures or a decreased interest in reporting minor contaminations. As a consequence of atmospheric weapons testing, there is a slowly decreasing level of ^{137}Cs in the environment and food that results in man now having a body burden of ~25 pCi/g of potassium, which delivers an annual radiation dose of about 0.5 mrads (NCRP, 1977a).

The most effective means for removing radioactive cesium in man is the oral administration of ferric cyanoferrate (II), commonly called Prussian blue, or Berlin blue, or ferric ferrocyanide (Madshus *et al.*, 1966; Madshus and Strömme, 1968; Strömme, 1968; Richmond, 1968; Stather, 1972; NCRP, 1977a). Although it is not available as an approved drug in the United States, it has been found to be relatively harmless and well tolerated by man (see Section 7.3.2.6). Other compounds related to Prussian blue, such as nickel ferrocyanide anion exchange resin, are also effective (Iinuma *et al.*, 1971) and without adverse reactions. Prussian blue is not absorbed from the intestine and it binds the cesium ions that are enterically cycled into the gastroin-

testinal tract so that the cesium is not reabsorbed. The biological half-time during such treatment is reduced to about one-third of its usual value and the body burden is likewise reduced. The effectiveness of the procedure is therefore dependent on the length of treatment and how soon after exposure it is started.

6.5 Cobalt

Cobalt, (Co), element number 27, has 10 radioactive isotopes, ^{54}Co to ^{64}Co. The radionuclides most likely to be encountered are ^{60}Co, ^{58}Co, and ^{57}Co. Cobalt-60 is the activation product produced by the bombardment of stable ^{59}Co by neutrons. Its half-life is 5.3 years and it decays by emitting a 0.31 MeV beta ray and gamma rays of two energies, 1.17 and 1.33 MeV. The other isotopes have shorter physical half-lives, ^{57}Co being 271 days, and ^{58}Co, 71 days. Both decay with the emission of penetrating gamma rays.

Cobalt-60 sealed sources are used in medical radiation therapy and industrial radiography. It is also used in industry for thickness gauges, calibration sources, and tracers. In biology, the radioactive cobalt isotopes have been used particulary for labeling vitamin B-12.

Small quantities of ^{60}Co and ^{58}Co have been detected in persons working around nuclear facilities, especially reactors, fuel-reprocessing plants, nuclear waste management operations, and laboratories using radioisotopes (Sill *et al.*, 1964; Edvardsson, 1972; Bhat *et al.*, 1973). Exposures usually have occurred by inhalation of particles. These are detected and evaluated more readily by whole-body counting techniques than by measurement for cobalt radioactivity in the urine. After inhalation exposure, about 80 percent of cobalt isotopes are eliminated with a biological half-time of one day or less (Edvardsson, 1972; Sill *et al.*, 1964). The remainder is eliminated much more slowly, varying considerably from case to case due presumably to chemical and particle size differences. Sill *et al.*, (1964) found biological half-times varying from 70 to 177 days. In one case the effective half-time was two years. Edvardsson (1972) found a second component in the elimination amounting to 5–10 percent of the total activity that had a biological half-time between 5 and 30 days. A third component in one case gave a biological half-time of about 200 days. Newton and Rundo (1971) studied 5 men who had inhaled cobalt metal or its oxide for periods of up to 11 years; the biological half-times in their chests ranged from 1.4 years to 17 years. Other studies by Cofield (1963) and Gupton and Brown (1972) gave lung clearance half-times of 3 months to 2.5 years.

A typical excretion curve for inhaled ^{60}Co is shown in Figure 4.1 (page 53).

Intravenous $^{60}CoCl_2$ administered to human subjects was retained for long periods, as much as 9 to 16 percent of the dose being eliminated with biological half-times of about 2 years (Smith *et al.*, 1972). The absorbed fraction of an oral dose was retained by the whole body similarly to ^{60}Co given intravenously. The absorption of orally administered $^{60}CoCl_2$ was 5 percent or less when only small amounts of stable cobalt (<1 μg Co) accompanied the dose, but increased to more than 20 percent when larger quantities of stable cobalt (1.2 mg) were given. About ⅕ of the total body content of ^{60}Co after oral or IV administration is retained in the liver.

These various studies in humans suggest that an appreciable fraction of cobalt isotopes is retained with a much longer biological half-time than the value of 10 days used by the ICRP (1968).

There have been no cases of significant radiation exposures resulting from internal deposition of cobalt radionuclides. No treatment of cases has been necessary. For ingestion, however, stomach lavage followed by a small or medium sized meal is indicated. Chelating drugs do not penicillamine (Section 7.3.5.5) can be considered in the case of a serious exposure where even small gains would be helpful. It should be used as soon as possible after exposure.

6.6 Curium

Curium, (Cm), element number 96, has thirteen isotopes, ^{238}Cm to ^{250}Cm. Because of their good power-to-weight ratio, high specific activity, and insensitivity to temperature variations, curium isotopes have been used in thermoelectric generators for unmanned meteorological stations and some aerospace satellites. Their principal use now is as a source material to be irradiated in high flux neutron fields in order to produce transplutonics such as berkelium and einsteinium.

Curium's high specific activity causes spontaneous heat release in addition to the hazard of its energetic alpha particles, neutrons, and gaseous daughter products. Heat production by ^{242}Cm is 120 watts/g and solid compounds may generate enough heat to reach a red glow due to self-irradiation. It also undergoes spontaneous fission with the release of two to eight fast neutrons per fission; the fission half-life is 1.3×10^7 years.

Curium-244 has a wider distribution in industry than most of the other curium isotopes because it has been used in thermoelectric

generators. It is produced in nuclear reactors during the irradiation of ^{242}Pu and can be recovered from the processed waste.

In general, curium compounds tend to be more soluble than their plutonium analogues. The critical organ for soluble curium compounds is bone, where the effective half-life for ^{244}Cm is 16.7 years. The effective half-life for ^{242}Cm is only about 155 days due to its short 163-day physical half-life, while ^{245}Cm with an extremely long physical half-life, 9300 years, is assumed to have an effective half-life of 199 years.

The absorption of soluble curium salts from the lung is rapid. Fifteen minutes after rats completed an inhalation exposure, 15 to 45 percent of the amount retained in the lung had passed through the alveoli and 10 percent had been deposited in bone (Nenot, 1971). The plasma clearance rate of curium is more rapid than for plutonium and less influenced by chemical form (Turner and Taylor, 1968).

After injection of the soluble ^{244}Cm citrate in beagles, initial excretion was almost entirely in the urine but later, reflecting liver uptake and excretion, it was excreted almost equally in the feces and urine (Lloyd *et al.*, 1973).

In general, curium, like the other transplutonic elements, seems to be more mobile than plutonium and thus irradiates soft tissues to a greater degree (Stannard, 1975). The large uptake by the liver is distributed diffusely within the organ. The uptake in the bones is greatest on surface mucoproteins in areas of enchondral ossification (Simon, 1972).

Since curium compounds tend to be soluble, DTPA therapy should be started as quickly as possible after exposure. Desferrioxamine (DFOA) does not reduce the retention of ^{244}Cm (Taylor, 1967; Volf *et al.*, 1977) and is not recommended.

Two cases of human exposure to ^{244}Cm have been reported (Sanders, 1974). One worker inhaled airborne particles of a poorly identified but relatively soluble aerosol containing curium. Four and one-half hours after the incident, 14 nCi were estimated to be in the lung by using the technique of *in vivo* chest counting of the 40 keV x-ray emission. One gram of CaDTPA was administered 2½ hours after the incident and the lung burden dropped to 5 nCi within four days.

In the other case, a worker inhaled mixed oxides of curium and americium. Three hours after the incident, the lung was estimated to contain 456 nCi, but 24 hours later it appeared to contain 1523 nCi, even though no further exposure had occurred. This delayed increase in activity is not an unusual finding when low-energy x rays from alpha emitters are being counted in the thorax. Such a change may represent merely a shift in counting geometry due to the relocation of the

radioactivity in the lungs. During the first seven days, 202 nCi were excreted in the feces. DTPA was given promptly and may have increased the excretion. DTPA was not given again until the fiftieth day after the incident, when 99.8 percent of the soluble ^{244}Cm had already been excreted. At that late time it was not particularly effective.

6.7 Gold

There are twenty-four radioactive isotopes of gold, (Au), element number 79, but ^{198}Au is the only one that is used widely in medical therapy, biological research, and occasionally as a calibration source. It is produced by bombardment of stable ^{197}Au with neutrons. Gold-198 emits 0.97 MeV beta particles and, in 95 percent of disintegrations, 0.412 MeV gamma rays; its half-life is 2.7 days.

For medical uses, ^{198}Au was formerly used primarily in a colloidal form. The principal therapeutic use of ^{198}Au colloid was in the palliative management of malignant pleural, abdominal, and pericardial effusions. Approximately 90 percent of the radiation dose is delivered by the beta particles which have a mean penetration of about 0.4 mm and a maximum of less than 4 mm in tissues.

When non-colloidal ^{198}Au solutions are taken in by mouth, about 10 percent is absorbed into the blood. Of this about one quarter goes into the liver and kidneys (Simon, 1972). Gold is eliminated from the body via the feces and the urine.

Colloidal gold injected intravenously is distributed differently and little is excreted within the effective half-life of 2.6 days. The phagocytic reticulo-endothelial (R-E) cells of the liver, spleen, bone marrow, and lymph nodes quickly remove the colloid from circulation (Säterborg, 1973). While there is some dependence upon particle size, the R-E cells of the liver retain about 80 to 85 percent, the spleen 5 to 10 percent, and the other tissues the remainder of the usual commercial preparation.

In accident situations, the organ dose calculations must take into consideration the widely varying distribution of gold depending on whether the material is in the ionic or colloidal form and the route of administration. It was not possible to do this in the simple presentation of doses in Table 2.6 (page 14); therefore, dose must be recalculated to account for the estimated organ distribution in an accidental exposure case.

If a therapeutic dose of ^{198}Au had been injected into a patient shortly prior to his death, the pathologist would have to evaluate the quantity present in the peritoneal or pleural fluids prior to proceeding with an autopsy. Proper procedures can be found in NCRP Report 37 (1970).

No industrial type accidents have occurred that resulted in ^{198}Au exposures. Two instances of misadministrations of ^{198}Au resulted from carelessness in ordering the ^{198}Au colloid and in administering intravenously the therapeutic preparation in place of the diagnostic (Baron *et al.*, 1969). The doses were 200 and 120 millicuries instead of the intended 200 and 120 microcuries, respectively. The calculated dose to the liver and spleen from 200 millicuries was 7,300 rads; the bone marrow received an estimated 440 rads. It was bone marrow failure that led to death 70 days later from intracerebral hemorrhages due to severe thrombocytopenia. The thrombocytes, in contrast to the other cellular elements of the blood, showed little evidence of recovery. Liver function tests gave no signs of deterioration of that organ, but with further time hepatic damage may have occurred.

There is no known therapy that is useful for ^{198}Au colloid, once the particles are phagocytized by R-E cells. Bone marrow failure might be treated with transfusions of suitable blood components. For gold in ionic solution, dimercaprol (Section 7.3.5.4) or penicillamine (7.3.5.5) may be tried although the short effective half-life of ^{198}Au suggests that the dose reduction resulting from these agents will be limited.

6.8 Iodine

Of the more than 20 radioactive isotopes of iodine, (I), element number 53, about half occur as fission products, and among them, ^{131}I contributes an increasingly important portion of the total activity starting at several hours after fission. The dominant internal exposure after a reactor accident or nuclear weapons test or any incident involving fresh fission products is likely to be ^{131}I (Roberts, 1966). However, the short-lived radioisotopes, ^{132}I, ^{133}I, ^{134}I, and ^{135}I, with half-lives from 52 minutes to 6.7 hours, can contribute significantly if the person is in close proximity to a fresh fission product release.

Iodine-131 has a physical half-life of about 8 days and an effective half-life in humans of about 7.6 days. It decays by emitting beta particles of four energies [0.25 to 0.81 MeV, the predominant one is 0.61 MeV (87.2 percent)] and gamma rays of five energies [0.08 to 0.72 MeV, the predominant one being 0.36 MeV (79 percent)]. The effective energy is generally taken as 0.22 MeV. An important shorter-lived iodine found in fresh mixed-fission products is ^{132}I, which is derived via ^{132}Te, a 78-hour half-life beta emitter. Iodine-132 has a 2.3-hour half-life and decays with six betas (0.80 to 2.14 MeV) and many gamma rays (0.38 to 1.39 MeV). Although the following discussion centers on ^{131}I, the metabolism and treatment is applicable to the other radioac-

tive iodines. Only the risk (dose) estimate changes as the mixtures of iodine isotopes shift according to their effective half-lives and energies.

In a reactor accident involving fuel rod leakage, a sizable fraction of the inventory of ^{131}I becomes available because of its volatility. In a major reactor accident, the containment vessel is designed to retain nearly all of such vapors. In the Windscale reactor fire in England in October 1957, it was estimated that 20,000 Ci of ^{131}I were released through a 410-foot stack (Dunster *et al.*, 1958). This air-cooled reactor had no containment features to retain volatile products. In weapons tests, each kiloton of fission energy produces 30,000 Ci of ^{131}I (Holland, 1963). Iodine may be released from ruptured fuel elements, during dissolution of spent fuel elements (Sill and Flygare, 1960), from leaks (Bhat *et al.*, 1973), and malfunctioning ventilation systems (Frederickson, 1970). Exposures may also occur during manufacture of iodine radiopharmaceuticals and sources (Soldan, 1968), during research, and in transportation accidents (Paas, 1967). Due to its volatile character and ease of absorption, potentially exposed persons should be monitored after any accident where release of radioactive iodines is suspected.

Small exposures usually occur as the result of inhalation, but ingestion through mouth pipetting (Haas, 1970) and absorption through the skin have been reported (Low, 1970; Harrison, 1963). When extensive environmental contamination occurred during the Windscale reactor accident in 1957, and after the Sedan and Dominic II nuclear tests in Nevada (Bernhardt *et al.*, 1971), contamination of the milk supply by cattle grazing on contaminated grasslands was a major problem. Fall out from atmospheric nuclear weapons testing exposed the residents of certain of the Marshall Islands to external radiation and to radioiodine by ingestion (Conard *et al.*, 1970; 1975).

In view of the quantity produced, transported, and used, it is a tribute to the care and precaution used in industry that only 20 cases of internal exposure to radioiodine were reported to the AEC by its contractors during the period 1957–66. Sixteen of these cases occurred as the result of two incidents, one at a chemical processing facility and the other after an underground nuclear detonation. Only 11 exceeded the permissible dose and none caused obvious injury (Ross, 1968). During the same period, six cases occurred among AEC licensees. All but one of these were the result of processing activities; the one exception happened during a gas release from a defective fuel element (Roeder, 1968).

Most of the iodine in accidents will be soluble and quickly absorbed via inhalation, ingestion, or the skin or any combination of these.

Inhaled iodine reaches equilibrium with body fluids in about ½ hour (Ramsden *et al.*, 1967). The mean values for normal 24-hour ^{131}I thyroid uptake in six test groups in the United States ranged from 12 to 20 percent of the total oral dose (Ghahremani *et al.*, 1971). The percentage of the dose of radioiodine that is present in the thyroid gland one day after ingestion is similar for children and adults (Van Dilla and Fulwyler, 1964). Even though the adult thyroid gland is considered a relatively radioresistant organ, radiation exposure has resulted in an increased frequency of nodules and cancers (Conard *et al.*, 1970; 1975; UNSCEAR, 1977). Patients who received 3 mCi or less for the treatment of hyperthyroidism have developed hypothyroidism, some as late as 17 years after treatment (Glennon *et al.*, 1972).

The maximum permissible organ burden for continuous exposure to ^{131}I is 0.7 μCi in the thyroid (NCRP, 1959; ICRP, 1960) or a thyroid dose of 15 rems per year. In cases of environmental contamination with radioiodine where the ^{131}I is transferred via grass → cow → milk → man, the physician may be called upon to advise patients on the safety of drinking milk after a reactor accident. In general, there is about a 5-day effective half-life of ^{131}I on vegetation (eight-day physical half-life combined with a 14-day vegetation half-life, varying with growth rate and weathering) (FRC, 1964). An infant drinking one liter of milk per day contaminated to an initial level with 1 μCi/l will receive a total cumulative dose to the thyroid of about 16 rems (FRC, 1964).

When environmental contamination of pastureland occurs, effective protective actions include changing the cow forage from contaminated to uncontaminated feed, withholding milk from consumption, and diverting milk from direct use to milk products, such as cottage cheese, firm cheese, condensed milk, or powdered milk (Bernhardt *et al.*, 1971; White and Moghissi, 1971). Emergency reference levels have been suggested that can be used to determine when countermeasures may be indicated. These levels are 0.25 μCi/1 as a peak level in milk and 1.5 μCi/m^2 on pasture (Bryant, 1969).

Preventive actions to reduce exposure to radioactive iodine from milk must be taken promptly if they are to be effective. Sensitive and rapid field methods for monitoring contamination of milk have been developed (Porter and Carter, 1965). Techniques for the routine monitoring of milk from cattle grazing in pastures surrounding a reactor are now required to detect the very low concentration of 0.25 pCi/1 (USAEC, 1973). Means of protecting the thyroid gland after nuclear reactor accidents are discussed in NCRP Report 55 (1977b).

When a person has been exposed to radioiodine the thyroid gland can be monitored for radioactivity by holding a beta-gamma detector

close to the suprasternal notch. If the detector is a NaI crystal plus pulse height analyzer and calibrated with a phantom, reasonably accurate estimates of thyroid uptake can be made. Counts made soon after exposure often may be unreliable because of skin contamination. A scan of the thyroid in the Nuclear Medicine Department of a hospital will give a qualitative estimate of exposure and properly calibrated instruments used for radioiodine uptake studies can be used for a quantitative figure. The usual limit of detection is below the 1–2 μCi level. Urine bioassay can be used to measure excretion. Whole body counting will detect 3×10^{-4} to 3×10^{-3} μCi (Mehl and Rundo, 1963).

Individuals who have had an accidental occupational exposure to radioiodine, regardless of the route of exposure, should immediately be given a 300 mg KI or NaI tablet,[1] which provides 230 and 255 mg respectively of the stable iodide. Five or six drops of SSKI, Saturated Solution of Potassium Iodide, (1 g/ml) in a small glass of water is another convenient means to administer the stable iodide. Iodates, such as KIO_3 or $Ca(IO_3)_2$, are also effective (Auxier and Chester, 1972), but are not available as FDA-approved drugs. See Section 7.3.4.2 for additional discussion on the use of antithyroid drugs for exposure to radioactive iodine.

Daily administration of 300 mg KI should be continued for 7 to 14 days. This continuation of the blocking agent is needed to prevent recycling of the radioiodine (Bernhardt *et al.*, 1971). A combination of KI and thyroid stimulating hormone has been used but this offers little advantage over simple KI given promptly (Blum and Eisenbud, 1966).

Individuals exposed to large amounts of ^{131}I should be observed periodically for evidence of hypothyroidism, which may not develop for several years (Glennon *et al.*, 1972). The amount required to produce early myxedema in a patient with normal thyroid function is in excess of 150 μCi per gram of estimated thyroid gland weight (Chapman, 1965). For thyroid exposures in excess of 100 rads, an estimate of residual thyroid function should be made within two or three months after exposure by measurements of plasma T_4 and TSH by radioimmunoassay. At six months to yearly intervals thereafter, measurements of plasma T_4 and a clinical evaluation should be made.

[1] In general population exposures to ^{131}I, the NCRP (1977b) recommends a daily dose of 130 mg of potassium iodide for adequate blocking of the thyroid. One-half of that dose should be given to children under one year of age. In known occupational exposures to radioactive iodine discussed here, a slightly improved therapeutic effect can be gained by the higher stable iodide dose recommended here without a significant increase of side effects.

6.9 Mercury

Five radioactive isotopes of mercury, (Hg), element number 20, are produced by exposing mercury or mercury oxide to neutron bombardment. All but two have half-lives of less than a day. The longest-lived mercury radioisotopes are ^{203}Hg and ^{197}Hg with physical half-lives of 47 days and 65 hours, respectively. Mercury-203 decays by emitting a 0.21 MeV beta particle and a 0.279 MeV gamma ray. Mercury-197 decays by orbital electron capture with emission of two x rays (0.077 and 0.19 MeV).

Both isotopes have been used in nuclear medicine for scintigraphy of the kidneys or brain, but have been replaced now by other agents. Mercury radionuclides are used in biological or medical research laboratories. They are found occasionally in industrial settings, such as areas related to mercury isotope production around nuclear reactors or in radiopharmacies.

The effective half-life for ^{203}Hg is usually considered to be 11 and 8.2 days for the kidneys and whole body, respectively (ICRP, 1960). Investigations of exposure to different chemical forms of ^{203}Hg and by various means of administrations have indicated effective half-lives from 19 to 30 days (Edvardsson, 1972; Johnson and Johnson, 1968; Roedler *et al.*, 1972; Rahola *et al.*, 1972; and Scott, 1969). After accidental inhalation of elemental ^{203}Hg by two laboratory workers, the effective half-lives were found to be 16.6 ± 0.6 and 17.5 ± 2.0 days (Brown *et al.*, 1975).

Accidental exposures to mercury radionuclides have thus far not involved doses large enough to require treatment. In view of the relatively short effective half-lives, the available therapy may not prove to be of much value. In case of ingestion, gastric lavage should be the single most useful procedure if done within the first hour. Dimercaprol (Section 7.3.5.4) and penicillamine (Section 7.3.5.5) can enhance excretion of mercury. Sodium-2,3-dimercaptopropane-1-sulphonate was found to be clearly superior to various other chelating agents in the case of inorganic mercury (Gabard, 1976a) and methyl mercury (Gabard, 1976b) in rats.

6.10 Phosphorus

Phosphorus-32 (^{32}P) was the first radioactive isotope to be prepared in a cyclotron for biologic and therapeutic research purposes and was produced by irradiating red phosphorus, element number 15, with deuterons (Cohn and Greenberg, 1938; Lawrence *et al.*, 1939). This

product had a low specific activity, whereas practically carrier-free ^{32}P now is separated chemically from a target of sulfur-32 irradiated with neutrons. The physical half-life of ^{32}P is 14.2 days. It decays by emitting a beta particle with a maximum energy of 1.71 MeV and an effective mean energy of 0.69 MeV corresponding to a maximum range in tissues of 7 mm and a half-value layer in tissue of 2 mm.

Phosphorus is an essential element in living cells and, in standard man, the phosphorus content is listed as 1.1 percent of the body weight, or 780 g (ICRP, 1975). It is eliminated from the body principally via the urine. For soluble compounds of ^{32}P, the critical organ is the bone, which receives about 20 percent of the dose ingested or inhaled. Tissues with rapid cellular turnover rates also show higher retention due to the concentration of phosphorus in the nucleoproteins. This concentration has been used to provide a possibly useful differential localization pattern for certain nuclear medicine procedures. A long biological half-time for phosphorus, ~257 days for the whole body and 1155 days for bone, makes the effective half-life for ^{32}P about the same as its physical half-life, 14 days.

Phosphorus-32 is used widely in medicine, biochemical research, industry, and agricultural research. It is used in medicine for both diagnostic and therapeutic purposes. Although once used in the diagnosis of intraocular, intracranial, skin and breast tumors, this use has been supplanted by improved techniques designed around the specific characteristics of other radionuclides. Phosphorus-32 is used as a therapeutic agent for the treatment of polycythemia vera in initial doses of 50 to 100 μCi/kg of body weight of an isotonic solution of $Na_2H^{32}PO_4$ given intravenously or orally. In biochemistry, industry, and agriculture, ^{32}P is used as a tracer to study phosphorus-containing processes, such as nucleotide biochemistry or fertilizer utilization.

Serious accidental exposures to ^{32}P have not been reported from its use except due to misadministration in medical use. An accidental overdose of ^{32}P to a patient being treated for thrombocytosis occurred because the month of the assay of the stock solution was recorded on the bottle erroneously as 9 for September instead of 10 for October with the result that 16.2 mCi were administered instead of 4.05 mCi (Cobau *et al.*, 1967). The characteristic fall of white and red cells developed progressively for six weeks after exposure. Recovery began on about the forty-fifth day and was not quite complete 300 days later. The patient was free of symptoms throughout the entire course of the syndrome. Treatment in this case was begun on the ninth day after ^{32}P administration, shortly after the error was discovered. The therapy, continued over an 18-day period, included large doses (5 g) of phosphate by mouth daily as the buffered sodium salt (Section 7.3.3.4),

calcium (540 mg) given intravenously daily (Section 7.3.3.6), and 200 units of parathyroid extract intramuscularly every 6 hours (Section 7.3.4.6). This regimen, although started late, resulted in an estimated 38 percent reduction of radiation dose to the bone marrow.

Recommendations for treatment of non-radioactive phosphorus poisoning by ingestion are included here for consideration in the case of accidental ^{32}P ingestion. Treatment immediately after ingestion of stable phosphorus, according to Arena (1976), should include thorough gastric lavage with potassium permanganate (1:5000) or 3 percent hydrogen peroxide. Copper sulfate, which forms insoluble copper phosphide, may be given in a dose of 0.25 g in a glass of water. Mineral oil (100 ml) will help prevent absorption and hasten elimination. This can be repeated in 2 hours. Use of aluminum hydroxide gel or aluminum phosphate gel (Section 7.3.2.7), or a mixture of aluminum and magnesium hydroxide, can also be used to help prevent gastrointestinal absorption.

6.11 Plutonium

Plutonium, (Pu), atomic number 94, a transuranic element, is a silvery-white reactive metal that melts at 639.5°C and oxidizes readily on warming in moist air. In powdered form the metal may be pyrophoric, igniting spontaneously in the range of 300° to 350°C. Of its 15 isotopes (^{232}Pu to ^{246}Pu), all of which are radioactive, ^{238}Pu and ^{239}Pu are the most likely to be encountered.

Plutonium-239 is an alpha emitter with a 24,400-year physical half-life. It emits two principal alpha rays [5.16 MeV (88 percent) and 5.11 MeV (11 percent)], which are accompanied by infrequent gamma rays [e.g., 0.039 MeV (0.0012 percent)]. A mass of ~16 g of ^{239}Pu equals one curie of radioactivity. Plutonium-239 has the property of fissioning when exposed to a slow neutron flux. This is the basis for its use as a fissile fuel for nuclear explosives and for generating heat for power production (Weast, 1975).

Plutonium-238 has an 86-year physical half-life and is finding increased use as a heat source because of its high rate of emission of alpha particles. A mass of ~57 mg equals one curie of radioactivity. The principal alpha emissions have energies of 5.50 MeV (72 percent) and 5.46 MeV (28 percent). Plutonium-238 has been used in thermoelectric generators as a power source for lunar space missions, communications satellites, heart pacemakers, and experimental power sources for artificial hearts (Bair and Thompson, 1974). On a mass basis ^{238}Pu

is 280 times more hazardous than ^{239}Pu because of its greater radioactivity per unit mass.

From a biological standpoint the high chemical reactivity of plutonium is an important characteristic. Plutonium can exhibit five oxidation states from a valence of +3 to +7 (Taylor, 1973). It has a marked tendency to hydrolyze and to form complex ions under physiologic conditions. The compounds formed may be monomeric, in which state any particulates are less than about 0.01 μm in diameter, or polymeric with particle diameters ranging from about 0.01 μm to over 1 μm. In the body, monomeric compounds become converted to at least minimally polymeric forms. Hydrolytic reactions also can change the chemical form after intake. Biological ligands to which plutonium may bind in the body include proteins, apoferritin, amino acids, phospholipids, hydroxy acids, and other metabolites (Taylor, 1973). Polymers and particulates formed by hydrolysis lead to binding on cell surfaces and phagocytic uptake of plutonium.

Because of the unique history of plutonium as a man-made element, it was possible to consider its potential biological hazards and to impose controls for personnel protection from the start. Radiobiological research on the effects of plutonium has been extensive (Bair and Thompson, 1974; Vaughan *et al.*, 1973; Bair *et al.*, 1973). The principal routes of entry to the body are through inhalation and contaminated wounds; ingestion and contaminated intact skin result in little absorption and are not important modes of exposure. After entry into the body some or all of the plutonium is solubilized by the body fluids, including blood, and redistributed within the body. The rate and amount of plutonium translocation will be markedly influenced by the deposition site, the physical and chemical form of the deposited compound, and the specific activity of the material. Ultimately, the plutonium will be distributed by the blood to the skeleton, liver, and all other tissues in the proportion 45: 45: 10 percent, respectively (ICRP, 1972). The retention half-time in the whole body has been estimated to be about 200 years in man (Langham, 1959; Durbin, 1972), and the half-times in the skeleton and liver are assumed to be 100 years and 40 years, respectively (ICRP, 1972).

The portal of entry of plutonium into the body is the chief determinant of the course of the subsequent contamination and appropriate therapeutic efforts. The unbroken skin surface offers high resistance to penetration by plutonium except mechanically as by a contaminated metal splinter or glass chip. Experiments on the unbroken skin of animals and man with various solutions of plutonium being applied for one day indicated that 0.002 to 0.25 percent of the applied plutonium was absorbed (Vaughan *et al.*, 1973). Subdermal or intradermal pene-

tration, such as in contaminated wounds, may result in long-term localization of the plutonium at that site and the possible appearance of a fibrous nodule (Lushbaugh and Langham, 1962; Lushbaugh *et al.*, 1967). The possible development of a sarcoma or carcinoma in such nodules is a matter of concern, although none has been reported to date. Contamination of wounds that have penetrated the skin may also lead to translocation of some of the material to the liver and skeleton. Ingestion of plutonium results in the absorption of approximately 0.003 percent by the intestine (ICRP, 1972).

Inhalation is a particularly important route of intake as it accounts for about 75 percent of industrial exposures (Ross, 1968). The amount retained in the lung is highly variable for it depends on the particle sizes and chemical form of the aerosol. If the compound is soluble, e.g., nitrate, citrate, fluoride, this retained plutonium may be largely absorbed into the blood circulation within a few weeks and translocated to the ultimate deposition sites, principally bone and liver. If the inhaled plutonium particles are relatively insoluble, e.g., in the case of high-fired oxides, their retention in lung tissue, pulmonary lymph nodes, and tracheobronchial lymph nodes will be high with a gradual translocation of small amounts over a period of months or years. In experimental animals, the pulmonary retention half-time is about 150 days for plutonium chloride and ammonium plutonium-pentocarbonates, 200 days for plutonium fluoride and citrate, 250 to 300 days for pulmonary nitrate, and up to 1000 days for PuO_2 (Bair *et al.*, 1973). Data on lung retention for plutonium compounds in man are not available in similar detail, but plutonium analyses of autopsy tissues from occupationally exposed workers show the highest concentrations per gram of tissue to be in tracheobronchial lymph nodes followed by lung and liver many years after inhalation exposure (Campbell *et al.*, 1973; 1974; Lagerquist *et al.*, 1973; and Norwood *et al.*, 1973).

There has been considerable experience in the management of persons exposed to plutonium. The cases can be classified as intact skin contamination, contaminated wounds, and inhalations; many cases are mixtures of these. Ingestion of plutonium has not been encountered as an exposure problem in industry, although cases of skin contamination or inhalation always involve the probability of some ingestion. Treatment is not required after ingestion because the low absorption rate does not result in any appreciable uptake in the body.

Plutonium contamination of intact skin is easily managed by washing with water, detergents, and occasionally other agents (see Section 7.1). Thousands of such cases have been cleaned up with no significant systemic absorption as long as the skin remains intact. Areas that are

not completely cleansed can be left alone after all loose material has been removed. Usually gloves or a temporary covering of some type are placed over the contaminated skin that resists cleanup attempts to retain the plutonium while the individual is at home or at work. It is not necessary to isolate the individual.

Contaminated puncture wounds and burns are a more serious problem because significant body burdens can result from these types of injuries. All wounds with possible plutonium contamination should first receive simple decontamination, such as washing and irrigating. The need for more extensive treatment by excision requires clinical judgment considering the skin area involved, ease of excision, and the quantity of plutonium in the wounds. Wounds containing over 4 nCi of plutonium should be serious candidates for such additional treatment. The treatment consists of immediate chelation therapy with CaDTPA, prior to surgical excision of the wound, to prevent possible systemic absorption (see Section 7.2). In wound decontamination, much attention is paid to locating the contaminating material as precisely as possible so that complete removal by surgical excision is accomplished with as little functional loss as possible. In burn cases, the burn surface shall be flushed with sterile saline or water. A large portion of plutonium in the burn area is likely to be removed later when the eschar sloughs off.

Review of human cases suggests that CaDTPA given immediately after wound deposition may result in urinary excretion of 50 percent or more of the material reaching the systemic circulation. The amount of plutonium that may transfer to the rest of the body within the first day or two will vary from only a few percent of that in the wound to well over 50 percent. Since this uptake cannot be predicted reliably in the usual accident situation, the use of CaDTPA is advised whenever the quantity in the wound is judged to be significant. A few illustrative cases are listed to show variations in treatment.

Schofield *et al.* (1974) reported the case of a wound in the right hand that was contaminated with an estimated 14 μCi of plutonium oxalate. Surgical excisions on days 1 and 14 were successful in reducing the content in the wound to about 1.5 μCi. Systemic CaDTPA therapy, a total of 13 grams during the first 14 days and at intervals throughout the next six months, is estimated to have diverted about half (~0.6 μCi) of the systemic plutonium absorbed from the wound into the urine. The CaDTPA intravenous administrations were usually given as 0.25 g per day with an upper dose of 1 g per day given at the time of the second excision.

In a review of several plutonium wound cases, Dolphin (1976)

concluded that CaDTPA therapy appeared to be more successful in cases involving contaminated wounds than in those involving inhalation.

Lagerquist *et al.* (1965) reported the treatment of a worker sprayed with an acid solution of plutonium chloride and plutonium nitrate that resulted in inhalation and ingestion of plutonium as well as skin and burn contamination. The skin, except for the burned areas, was decontaminated with dilute sodium hypochlorite solution. The patient received 11 one-gram doses of DTPA by intravenous injection beginning 1 hour after the accident and at intervals through day 17. Burn eschars were removed 2 weeks after the accident and were found to contain most of the plutonium. Treatments used in this case were considered highly effective. Prompt CaDTPA treatment was reported to be similarly effective in another contaminated acid burn incident (Lagerquist *et al.*, 1967a). Twenty-seven daily one-gram intravenous CaDTPA treatments, beginning 1 hour after the accident, resulted in elimination of more than 96 percent of the systemic burden. As in the previous case, much of the contamination was removed with the eschar.

The effectiveness of CaDTPA, using a regimen similar to those reported above, was considered inconclusive in the case of a wound in the thumb from a plutonium-contaminated metal sliver (Lagerquist *et al.*, 1965). Initially, the sliver was removed without tissue excision. On day 4, tissue excisions were performed at the points of entrance and exit of the sliver; the entry site contained about 98 percent of the plutonium removed by those excisions. Wound counting performed over several months indicated a movement of embedded plutonium toward the skin surface. Nodules that formed concurrently with increased wound counts were excised and found to contain essentially all the plutonium estimated to have remained in the thumb. While CaDTPA was effective in removing plutonium from the system, the continued presence of plutonium in the wound site indicates that the remaining relatively insoluble particles were probably not influenced by chelation therapy. McClanahan and Kornberg (1968) showed, in rats, that washing with CaDTPA would probably not accelerate greatly the removal of plutonium from contaminated wounds, nor would it increase the movement into the blood and so increase the amount retained systemically.

In the case of a puncture wound contaminated with plutonium-238 nitrate (Jolly *et al.*, 1972), CaDTPA was administered intravenously four days per week for about 11 weeks followed by a 32-week period of no treatment and then by a 90-week period in which CaDTPA (1 g) was administered intravenously or by aerosol on 2 successive days

each month. The wound area was excised 2 hours after the accident. The ^{238}Pu content in the body after wound excision was estimated to be 103 nCi. The CaDTPA treatment for more than two years was credited for the further reduction in the body burden to an estimated 31 nCi.

Additional cases of puncture wound injury have been reported (Lagerquist *et al.*, 1967b; Swanberg and Henle, 1964). In each instance of puncture wound, prompt CaDTPA therapy and one or more tissue excisions appeared to be effective.

The use of CaDTPA or ZnDTPA chelation is indicated for cases of plutonium aerosol inhalation, but the results have been disappointing in many instances. This is due to the fact that the chemical form most commonly encountered in aerosols is PuO_2. This compound is transferred at a relatively slow rate from the lung into the systemic circulation over many weeks or months. Thus there is little systemic burden of plutonium available for chelation in the early period after exposure and there is never a time when a sizable systemic burden is available in extracellular spaces for effective chelation.

In spite of this experience, CaDTPA should be used as soon as possible after significant inhalation exposures because the chemical form usually is not known in these accidents. The therapeutic effect on soluble forms is manifest principally in the first 12 to 24 hours and a therapeutic trial should be initiated immediately to insure that the patient will benefit from the treatment if some systemic uptake has occurred.

An estimate of the possible effectiveness of CaDTPA chelation therapy in persons who have inhaled plutonium particulates can be made based on the results of a relatively few cases treated to date. Norwood (1960, 1962a) showed the therapeutic effect of giving CaDTPA intravenously to seven individuals starting several years after inhalation exposure to plutonium. The rate of elimination of ^{239}Pu via the urine was increased 45 to 120 times and fecal elimination increased sixfold. Long-term administration in one case showed a gradually decreasing effectiveness until at the end of 50 weeks of intermittent therapy, it was only 20 percent as effective as it was at the beginning. About 20 percent of the estimated body burden of plutonium was removed by this long-term therapy when started 5 years after deposition (Norwood and Fuqua, 1969).

Data from two puncture wound cases and several inhalation cases treated with CaDTPA were used to derive an empirical urinary excretion model for single and multiple DTPA treatments (Hall *et al.*, 1978). The percentage of inhaled soluble plutonium excreted in urine both after a single and after five treatments is shown in Table 6.1. Figure 6.1 gives a plot of the predicted urinary excretion rates after a single

TABLE 6.1—*Predicted plutonium excretion in urine after inhalation of a soluble plutonium aerosol with and without CaDTPA treatment*

Week	Percent of initial systemic Pu deposition excreted in urine		
	No treatment	Single treatment[a]	Five treatments[b]
1	0.64	38	42
2	0.24	11	13
3	0.17	5.5	7.7
4	0.13	2.8	3.6
5	0.11	1.4	1.8
6	0.09	0.71	0.91
7	0.08	0.37	0.46
8	0.07	0.19	0.24
9	0.07	0.11	0.13
10	0.06	0.07	0.07
TOTAL →	1.7	60	70

[a] CaDTPA therapy (1 g in 4 ml by aerosol) on day one immediately after inhalation.
[b] CaDTPA therapy (1 g in 4 ml by aerosol) with optimal schedule on days 1, 2, 4, 7, and 15. (From Hall *et al.*, 1978.)

administration of CaDTPA immediately after or two days after an acute intake of soluble plutonium.

The Pu-DTPA excretion model has been used to evaluate bioassay data on five other workers exposed to airborne ^{238}Pu contamination and treated immediately with CaDTPA by aerosol. The excretion curves for the various treatment regimens predicted by empirical equations fit the bioassay results obtained for these cases reasonably well (Hall *et al.*, 1978). Good correlation was also found in a case of inhaled ^{239}Pu fluoride treated with 1 g of CaDTPA intravenously at 3 hours post-exposure and days 2, 5, and 8 post-exposure (Voelz, 1979). These models indicate that the DTPA therapy initiated immediately after a contamination incident may reduce the body burden of soluble plutonium by a factor of about 3.

In other accidental inhalation cases, chelation therapy with Ca-DTPA has failed to achieve a significant increase in the elimination of plutonium. These cases generally involve PuO_2, particularly the high-fired oxides. The gradual transfer of plutonium from the lung to other organs through the systemic circulation is reflected in a rising urinary excretion pattern of several months to years. Low plutonium values in urine for the first few weeks after this type of inhalation exposure can lead to a significantly low estimate of the lung exposure unless periodic urine samples are taken over a period of months and years. Figure 6.2 shows several such predicted excretion curves based on lung clearance half-times of 70 and 700 days. Schofield and Lynn (1973) found little effect in three cases given CaDTPA within a few hours following PuO_2

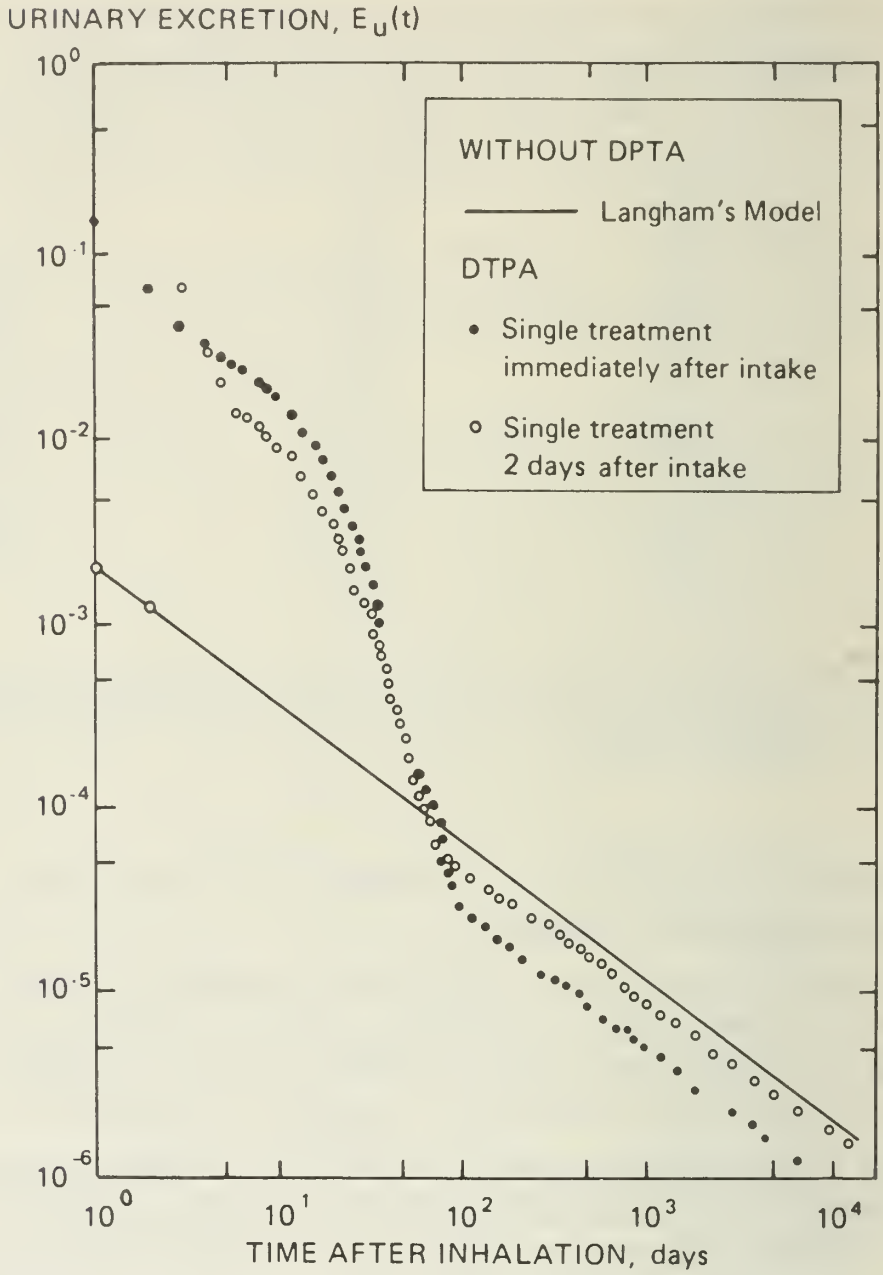

Fig. 6.1. Predicted urinary excretion rates (portion of body burden excreted per day) after single intake of soluble plutonium with DTPA administered immediately after and two days after exposure compared to that predicted by Langham's equation for untreated persons (Hall *et al.*, 1978).

inhalation. Catsch (1976) notes that "the efficacy of DTPA is extremely poor or even nil in the case of polymeric or highly insoluble compounds of the radionuclides. For instance, it is absolutely impossible by DTPA to remove PuO_2 from an intramuscular deposit or from the lung; this holds both for systemic and local administration of DTPA." Attempts to stimulate phagocytosis and the mucus-transport mechanism or to use expectorant drugs have not been successful in animal studies (Tombropoulos, 1964; Bair and Smith, 1969).

The only procedure that is useful in enhancing the clearance of insoluble particles, like PuO_2, from the lung is bronchopulmonary

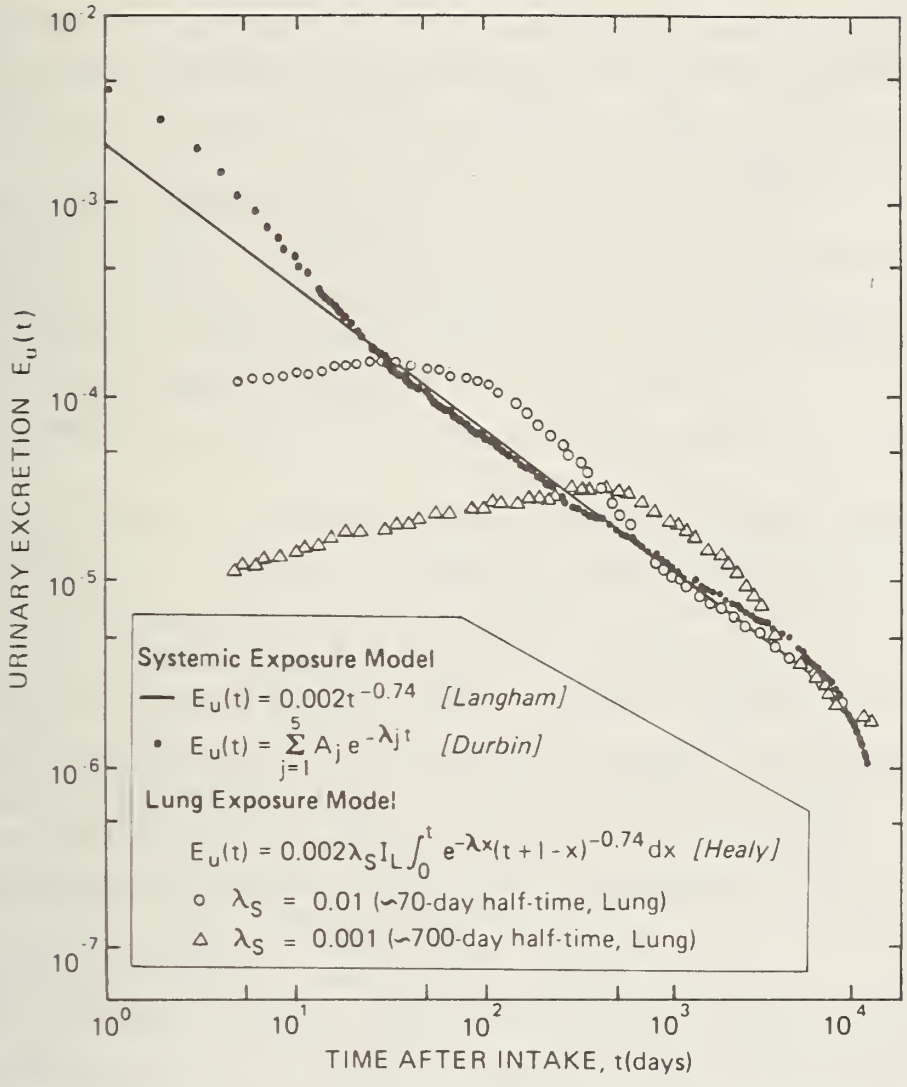

Fig. 6.2. Predicted urinary excretion rates (portion of body burden excreted per day) plotted as a function of time after an acute plutonium inhalation. The plots of Langham's and Durbin's equations represent excretion of the lung burden transfers to the blood immediately after exposure. The curves of Healy show predicted excretion when the lung to blood transfer occurs with half-times of ~70 and ~700 days (Hall *et al.*, 1978).

lavage (Section 7.4). Here the physician must balance carefully the risk of this procedure against the risk of future health effects created by the estimated lung burden (Section 5.2). Use of repeated lavages should be able to remove 25 to 50 percent of plutonium that would otherwise be retained in the lung.

6.12 Polonium

Polonium-210 was used extensively in early atomic weapons manufacture and later was employed briefly in thermoelectric generators in space satellites. The first communications satellite was powered by a

^{210}Po source. Polonium-beryllium neutron sources have now largely been replaced by plutonium-beryllium or transplutonic sources. Polonium-210 is used as a static eliminator (Robertson and Randle, 1974) in a variety of applications.

Polonium, element number 84, is a soft silvery-gray metal, much like lead in appearance. It volatilizes readily in a vacuum at elevated temperatures. When deposited on Pyrex glass or quartz, it eventually produces small irregular cracks called crazing (Goode, 1956). Therefore, old polonium ampoules should be considered hazardous. Polonium readily forms halides and many polonium compounds are relatively soluble.

The atmosphere normally contains polonium. It arises from radium-226, which occurs widespread in nature in the earth's crust (Hill, 1965). Contributions have been added by such man-made activities as burning fossil fuels, nuclear weapons testing in the atmosphere, and accidents such as the Windscale reactor accident. Grazing animals take up ^{210}Po from contaminated grass and concentrations greater than 1000 pCi/kg have been found in caribou in the Arctic (Hill, 1965). Marine organisms ranging from plankton to shellfish, crabs, and fish (Hoffman *et al.*, 1974) are often contaminated with ^{210}Po. Cigarettes have been found to contain 0.49 ± 0.07 pCi per cigarette (Hill, 1965) and it has been suggested as a possible cause of lung cancer (Marsden, 1964). Such information can be of some importance to the physician when he receives a bioassay report stating a low-level ^{210}Po content that cannot be explained on the basis of an occupational exposure.

Polonium-210, formerly called radium F, is the last radioactive member of the uranium-radium radioactive series and has therefore been extensively studied in uranium miners. After years of exposure, about 78 percent of the polonium body burden will be found in the skeleton with important deposits in the lung, liver, muscle, lymph nodes, kidney, spleen, and blood (Blanchard and Moore, 1971). This distribution probably is derived more from the preceding isotopes in the chain than from ^{210}Po itself.

Polonium-210 decays by alpha emission with a physical half-life of about 138 days. The biological half-time in the whole body is about 40 days (ICRP, 1968), while for the spleen and kidneys it is somewhat longer, about 60 and 70 days, respectively (ICRP, 1960). The longest effective half-life, 46 days, is in the kidneys. The critical organs are considered to be the spleen and kidneys (ICRP, 1960). Studies on several species of laboratory animals have shown the highest concentrations of ^{210}Po to be in kidney, ranging from 5 to 10 percent of the injected radionuclide (ICRP, 1968).

The metabolism of polonium chloride has been studied in terminal human cancer patients (Silberstein *et al.*, 1950). After intravenous

injection of 0.17 to 0.3 μCi/kg, ^{210}Po was eliminated in the feces at levels ten to twenty times higher than in the urine. Polonium chloride is poorly absorbed from the intestine after ingestion. In one experiment, the daily absorption through the skin was found not to exceed 2 percent of the amount applied.

Urine and fecal bioassays are required for monitoring of exposures since *in vivo* counting cannot detect less than 100 μCi and the maximum permissible body burden is 0.03 μCi. Urine radiochemistry can detect 0.1 pCi/1 (ICRP, 1968).

Two physicists who inhaled ^{210}Po after the rupture of a polonium/beryllium source were observed to excrete ten times more ^{210}Po in the feces than in the urine (Foreman *et al.*, 1958). Another contamination accident that occurred in a university print shop resulted from the cleaning of a device to eliminate static; in this incident the operators incurred no significant radiation exposures (Caruthers and Maxwell, 1971). Another small exposure was reported to have been due to accidental inhalation of ^{210}Po during the handling of an encapsulated source (Scott and West, 1975). No treatment was required. Approximately 3 percent of the 0.015 μCi burden was excreted in the urine with a biological half-time of 33 days. The initial fecal to urine ratio of 65 dropped to 20 about 20 days post-exposure.

Dimercaprol (Section 7.3.5.4) has been suggested as a treatment (Hursh, 1951; 1952). When it was given intramuscularly after a single intravenous dose of ^{210}Po, the total excretion in a ten-day period was twice that of the control animals and the polonium was shifted from the bone marrow, spleen, and testes into muscle. When rats were injected with a lethal dose of ^{210}Po (36 μCi/kg), the median survival time was 22 days, but when promptly treated with dimercaprol the median survival time was 89 days. The untreated animals died of hemapoietic failure, while much less effect was demonstrated on the white cell and platelet levels of treated animals. Russian investigators have reported some success with the use of dimercaprol derivatives in animal experiments, but the compounds are not available in the United States (Parfenov *et al.*, 1974; Erleksova, 1959).

Neither DTPA nor EDTA is effective in treating polonium internal contamination (Foreman *et al.*, 1958).

6.13 Radium

Radium, (Ra), element number 88, is a radioactive element that occurs in each of the major series of natural radionuclides and transuranic elements. Radium-226, a member of the decay chain of ura-

nium-238, has a physical half-life of 1620 years. It decays to radon-222 by emitting alpha particles of two energies [4.589 MeV (5.7 percent) and 4.777 MeV (94.3 percent)]. The ^{222}Rn then decays to polonium-218 followed by a series of active daughter elements that emit mixtures of alpha, beta, and gamma rays. The most important daughter products of Radium-226 are radon-222 (3.8-day physical half-life, alpha emitter, gaseous), bismuth-214 (20-minute physical half-life, alpha and gamma emitter), and lead-210 (22-year physical half-life, beta and gamma emitter).

Radium-226 is used as a radioactive source in medical practice and industry. Its primary value has been in the treatment of cancers by insertion of encapsulated needle sources directly into the tumor or by means of moulded applicators that hold the source next to the tumor. Industrial applications have included radium-beryllium neutron sources, radium for radiography, and luminous paints. The use of radium in all of these applications has been reduced greatly with the availability of safer and cheaper radioactive materials although many radium applications still exist.

After ingestion, about 30 percent of the radium-226 is absorbed (ICRP, 1960). Most of that absorbed is excreted within a few days after exposure; 95–98 percent is eliminated in the feces and 2–5 percent in the urine (Oberhausen, 1963). The radium remaining in the body is almost entirely deposited in the skeleton (Neuman *et al.*, 1955; Lloyd, 1961; Rowland, 1963). Norris *et al.* (1955) proposed that the retention of radium in the body can be described by a power function, $R_t = 0.54t^{-0.52}$ where R_t = amount of radium retained after the time t and t = time in days after injection. The effective half-life of radium is about 4.5 years for bone and 900 days for the whole body. About 65 percent of the ^{222}Rn formed as a decay product of radium in the body is exhaled (Oberhausen, 1963). This value is time dependent and the 65 percent value is for long times (years) after deposition. The expired air can be used in "radon breath analyses" for estimating the quantity of radium in the body. A review on the metabolism of ^{226}Ra in man has been published recently (Marshall *et al.*, 1973).

In the past, radium was the major radioisotope leading to serious levels of internal emitter exposure in man. Observations on this element have been the keystone to setting permissible burdens of other bone-seeking radionuclides (Evans, 1967). Ingestion of luminous paints containing radium occurred about the time of World War I and for several years thereafter as a result of workers pointing their brushes with their lips. The report of Martland *et al.* (1925) described the clinical effects of radium poisoning in the dial painters and led to the classic paper by Martland and Humphries (1929) on the development

of osteogenic sarcoma in 2 of 15 cases. This observation was the start of additional studies by Martland, R. D. Evans, and J. C. Aub of radiation oncogenesis due to radium.

In 1941, a task group assembled by the U.S. National Bureau of Standards selected 0.1 μg as a tolerance dose of ^{226}Ra for workers. The 0.1 μg, and, by definition, 0.1 μCi, of radium was that amount that could be contained in the body without clinical evidence of harm, and this residual body burden remains the standard maximum permissible body burden to the present time.

Several decades ago radium was used as a form of therapy in a group of patients in a state mental hospital (Miller and Finkel, 1968). Radium was also used in repeated doses for the treatment of hyperthyroidism (Loucks, 1930). Follow-up studies on nearly 300 radium dial painters over a period of many years revealed several types of malignant tumors, including osteogenic sarcoma, fibrosarcoma, carcinoma of the paranasal sinuses and mastoid, leukemia, and aplastic anemia (Hasterlik *et al.*, 1969; Finkel *et al.*, 1969). Cumulative mean skeletal radiation doses below 1000 rads were not associated with clinically significant radiobiological injury according to the data in the Massachusetts Institute of Technology series, which covers a time span of 40–50 years in more than 500 persons (Evans, 1974).

Immediate stomach lavage with a 10 percent magnesium sulfate solution is recommended in patients who have just ingested radium. This should be followed by daily saline purgatives with magnesium sulfate.

Little is known about the removal of ^{226}Ra once it is absorbed into the human body. Compounds that induce skeletal demineralization have been shown to increase the fecal excretion of ^{226}Ra (Aub *et al.*, 1938). This increased excretion of ^{226}Ra was induced by the concurrent use of ammonium chloride, thyroid extract, and parathyroid extract. The urinary ^{226}Ra excretion was only slightly increased. Each of these agents is a potent demineralizer that usually causes an increased excretion of the urinary calcium and this effect should be associated with an increase of excretion of ^{226}Ra in the urine. Since ammonium chloride is an effective demineralizing agent, this type of compound alone may be useful in increasing the urinary excretion of ^{226}Ra, but no data have been reported to support or deny this presumption. Orally administered calcium has only a slight effect on increasing the urinary ^{226}Ra excretion (Aub *et al.*, 1938; Spencer *et al.*, 1973a). One study showed that intravenously administered ACTH increases the urinary ^{226}Ra excretion but does not affect the fecal ^{226}Ra excretion (Spencer *et al.*, 1973a). In mice the excretion of ^{226}Ra could be increased by the use of sodium alginate (Humphreys *et al.*, 1972; Van der Borght *et al.*,

1971) but no data are available on the effect of alginates on the intestinal absorption or excretion of ^{226}Ra in man.

6.14 Strontium

Six of the 16 radioisotopes of strontium, (Sr), element number 38, are direct fission products of uranium. By far the most important is ^{90}Sr because of its long physical half-life, 28 years. It decays by emitting a 0.54 MeV beta particle and gives rise to yttrium-90 which emits a 2.25 MeV beta particle. Strontium-89, an indirect fission product of uranium, has a physical half-life of 51 days and decays by emitting a 1.46 MeV beta particle and 0.009 percent of the time a 0.91 MeV gamma ray. Another important isotope of strontium is ^{85}Sr, which is produced by bombarding a ^{84}Sr target with neutrons to produce an $^{84}Sr(n,\gamma)^{85}Sr$ reaction. Its physical half-life is 65 days and it decays by orbital electron capture giving rise to ^{85m}Rb, which immediately emits an 0.513 MeV gamma ray. With the shorter physical half-life and gamma emission, ^{85}Sr incorporation in the body results in a much lower absorbed dose for comparable activity than does ^{90}Sr incorporation.

Strontium-90 applied in the form of plaques is used for treatment of cutaneous lesions that are only a few millimeters in depth. Sources have been used in industry for thickness gauges by measuring the beta-ray backscatter from relatively thin sheets of paper, rubber, or metal. Strontium-90 has also been employed inappropriately in paints for luminous dials. Other industrial applications include sources used for static dust elimination by air ionization and ^{90}Sr titanate sources as compact heat sources. Large amounts are used for thermoelectric sources in buoys and similar devices where a long-lived, independent power source is needed.

Strontium-85 has been preferred to ^{90}Sr as a tracer in medical and agricultural research. Its principal use in nuclear medicine has been for study of the metabolism of strontium and for diagnostic bone scans.

Extensive studies have been carried out on the metabolism of radioactive strontium in animals and man because of the risks from the presence of ^{90}Sr in nuclear fallout due to atmospheric weapons tests and from the possible effect of escape of strontium into the biosphere during or after the reprocessing of used fuel elements. Information published by the ICRP (1968) suggests that after a single intake by mouth about one-quarter, and after inhalation one-third, of the radiostrontium taken in is absorbed into extracellular fluid and one-half of this is deposited in bone. Because of the high energy of the

beta particles emitted by the $^{90}Sr + {}^{90}Y$ sequence, the ^{90}Sr deposited in bone irradiates both calcified bone and the adjacent bone marrow. Information on the potential hazards of ^{90}Sr in causing bone tumors, leukemia, and genetic effects are presented by Copp *et al.*, 1947; Nilsson, 1962; Van Putten and DeVries, 1962; Barnes *et al.*, 1970; Loutit, 1967; McClellan and Jones, 1969; Frolen, 1970; Nilsson, 1970; and UNSCEAR, 1977.

The biological half-time of ^{85}Sr in man was found to be less than 250 days during the first 160 days after a single ingestion (Furchner *et al.*, 1962). The average long-term retention in bone was estimated to be about 8.4 percent of the administered dose. The biological half-time determined by the use of intravenous tracer doses of ^{85}Sr averaged 843 days (Cohn *et al.*, 1962); the biological half-time after accidental inhalation of ^{90}Sr was estimated to be 500 days (Cowan *et al.*, 1952). The ICRP dose calculations use much longer half-times of about 50 years for bone and 36 years for the whole body (ICRP, 1960). The resultant effective half-life for ^{90}Sr is about 15 years.

The number of industrial or laboratory cases of accidental incorporation of ^{90}Sr into man is small. Several accidental ^{90}Sr inhalations have been reported (Cowan *et al.*, 1952; Rundo and Williams, 1961; Stewart *et al.*, 1958; Fisher and Kellehar, 1963; Bradley *et al.*, 1964; and Volf, 1963). In a case of accidental inhalation of $^{90}SrCO_3$ (Rundo and Williams, 1961), the ^{90}Sr body burden was estimated to be 0.364 μCi at 2 days after exposure. Accidental exposure to ^{90}Sr-titanate powder (Bradley *et al.*, 1964) resulted in an initial body burden estimated to be 5.2 μCi. However, several days after the accident the ^{90}Sr body burden had markedly decreased to 0.16 μCi. Two cases of accidental ^{90}Sr nitrate inhalation resulted in nasal smears containing 10^{-4} and 10^{-2} μCi ^{90}Sr (Volf, 1963).

Treatment was given in three of these ^{90}Sr inhalation exposures. Bradley *et al.* (1964) gave oral ammonium chloride and intravenous calcium. Volf (1963) treated two persons with orally administered barium sulphate. In none of these cases did the retained ^{90}Sr body burden exceed the maximum permissible body burden of 2 μCi ^{90}Sr.

Since ^{90}Sr that is ingested is eliminated mainly via the intestine (Spencer-Laszlo *et al.*, 1963; Spencer-Laszlo *et al.*, 1964), it is helpful to determine the fecal as well as the urinary excretions of ^{90}Sr after accidental exposures. In the case of ^{90}Sr-titanate inhalation (Bradley *et al.*, 1964), the fecal ^{90}Sr accounted for 94 percent of the total ^{90}Sr excretion. Volf (1963) found the largest amount of ^{90}Sr in feces 1 to 2 days after accidental inhalation of ^{90}Sr nitrate.

The amount of ^{90}Sr that has accidentally entered the human body can be estimated by a simple method in which only a single 24-hour

measurement of the urinary excretion of ^{90}Sr and of calcium is needed (Samachson and Spencer, 1965). Data obtained with tracer doses of ^{85}Sr in man (Spencer-Laszlo *et al.*, 1963; Samachson and Spencer-Laszlo, 1962; Spencer *et al.*, 1960) were used to determine various factors based on the time after exposure up to 12 days and the 24-hour calcium excretion in urine for the individual. The radiostrontium 24-hour urinary excretion, multiplied by the appropriate factor, gives a reasonable estimate of the radiostrontium absorbed.

Several methods of treatment can be used to reduce the amount of radiostrontium absorbed from the intestine and to assist in its removal. Immediately after ingestion, aluminum phosphate (Section 7.3.2.7) can reduce absorption of radiostrontium as much as 85 percent (Spencer *et al.*, 1967; 1969a; 1969b) and is considered the drug of choice. Barium sulfate (Section 7.3.2.9) is a risk-free alternative drug that also causes significant reduction of intestinal absorption (Volf, 1963). Sodium alginate (Section 7.3.2.8) inhibits the absorption of acutely ingested radiostrontium, but its heavy viscosity makes it difficult to administer.

After absorption of radiostrontium has occurred, several compounds of stable strontium (Section 7.3.3.3) can be used as isotopic diluting agents to reduce uptake of radiostrontium. They must be given shortly after exposure. Large doses of calcium (Section 7.3.3.6) orally or intravenously will increase excretion rates and may be used as a substitute if strontium drugs are not available. The above treatments should be combined with administration of oral ammonium chloride to achieve maximum effect (Section 7.3.4.3).

6.15 Technetium

Of the isotopes of Technetium, (Tc), element number 43, ^{99m}Tc, is used more frequently in nuclear medicine now than the radioiodine isotopes. It was selected and introduced because of its suitability for diagnostic scanning. Its gamma ray (0.14 MeV), emitted as it decays to technetium-99, is easily detected with a collimated detector at any body surface. Its short physical half-life, 6.0 hours, makes the radiation dose very small for each use in diagnostic procedures.

Technetium-99m results from the decay of molybdenum-99, which has a 67-hour physical half-life and decays by emitting several beta particles of energy ranging from 0.45 to 1.23 MeV plus seven gamma rays with energies of 0.04 to 0.95 MeV. The ^{99m}Tc then decays by isomeric transition to ^{99}Tc which has a physical half-life of 212,000 years. The ingrowth and decay of the ^{99}Tc is of no concern because of the low specific activity resulting from its long physical half-life.

Technetium, at least as the pertechnetate, has a very short biological half-time, only 1 day for the whole body, 20 days in the kidney, and up to 30 days in the liver. After intravenous administration, approximately 30 percent of the ^{99m}Tc-pertechnetate is excreted in the urine over the first 24 hours. Animal studies have shown that pertechnetate ion is selectively concentrated in the thyroid gland, salivary glands, and stomach (Andros *et al.*, 1965).

Pharmaceutically prepared solutions and suspensions of ^{99m}Tc compounds can be obtained, but loss of activity between manufacture, dispatch, and use is a major disadvantage. Development of an aluminum hydroxide absorption column loaded with ammonium molybdate-99 solved the transport problem. Nuclear medicine laboratories now order a column every week or two and elute its ^{99m}Tc in the form of pertechnetate as needed. The ^{99m}Tc must then be converted into various chemical forms suitable for specific diagnostic tests. It is used in a great many chemical forms such as the pertechnetate.

There have been no reports of misadministrations or accidents with ^{99m}Tc that caused recognizable effects, probably because the radiation doses from millicurie amounts are so small. There have been instances of misadministrations due to confusion of the millicurie with the microcurie. In one instance, a molybdenum-99 charged alumina column was assembled in the inverted position, in spite of explicit instructions to the contrary, with the result that patients received chiefly ^{99}Mo instead of ^{99m}Tc. No effects were observed. It seems unlikely that accidental exposures to ^{99m}Tc will require treatment, but steps must be taken to be sure that the activity detected is due to ^{99m}Tc and not some other radioisotope, e.g., radioiodine, for which immediate treatment might be indicated. Exposures to the very long-lived ^{99}Tc, such as might occur during nuclear fuel processing or waste storage, seem to have low hazard potential. The effects of long standing body burdens, however, have not been examined by animal experimentation.

Administration of potassium perchlorate ($KClO_3$) is effective in displacing pertechnetate-99m ions from sites of concentration in the thyroid gland, salivary glands, and stomach (Andros *et al.*, 1965).

6.16 Thorium

Thorium-232, with a physical half-life of 1.39×10^{10} years, is the starting element for a decay series that ends with ^{208}Pb. The series is analogous to that of ^{238}U except that the daughters have short physical half-lives, with two exceptions, (R^{228}Ra-6.5 y and ^{228}Th-1.94), and consequently, relatively larger amounts of ionizing radiation are deliv-

ered to the tissue surrounding a particle. Thorium, (Th), element number 90, is used in ceramic glazes, optical glass, gas mantles, tungsten welding electrodes, and various metal alloys.

Thorium-232 was used formerly in the chemical form of $^{232}ThO_2$ as a radioopaque substance, ideal for angiography. The preparation sold under the trade name "Thorotrast" was a 25 percent suspension of finely dispersed ThO_2. It contained varying amounts of daughter radioisotopes and, consequently, was more radioactive than it would have been had the thorium ore been refined to yield pure ^{232}Th for preparing the $^{232}ThO_2$.

Since Thorotrast was a fine particulate, the reticulo-endothelial cells of the liver, spleen, and marrow as well as hepatic cells phagocytized it quickly. Enhanced contrast, especially of fine vessels, can be obtained with Thorotrast but the risk of hepatomas, angiosarcomas, osteosarcomas, and subpleural mesotheliomas caused Thorotrast to be supplanted by other radioopaque media.

No effective treatment is available to modify the distribution or absorption of injected Thorotrast. For other thorium forms, the chelating agents DTPA (Section 7.3.5.3) or DFOA (Section 7.3.5.6) may enhance excretion but are not likely to be sufficiently effective to warrant long-term therapy.

6.17 Tritium (Hydrogen-3)

Tritium is the only radioactive isotope of hydrogen, (H), element number 1. It decays to ^{3}He by emitting a beta particle with a maximum energy of 18 keV and an average energy of 5.7 keV. Its half-life is 12.3 years. Small amounts of the isotope are present normally in the atmosphere and biosphere, being produced by cosmic-ray reactions with nitrogen in the stratosphere and also from the spontaneous fission of elements on the surface of the earth. Atmospheric weapons testing has increased the tritium present in the environment. Before the nuclear age, water contained a ratio of 1 tritium atom per 10^{18} hydrogen atoms but this is now about 10 to 100 per 10^{18} hydrogen atoms.

Tritium has not been widely used in clinical medicine, probably because of the difficulty in detecting its weak beta particles. Experimental uses include total body water measurements and the *in vivo* labeling of proliferating cells by injection of tritium-labeled thymidine. Tritium labeling is also used in a variety of metabolic tracer studies. When it is incorporated in chemical compounds, the distribution and retention of that tritium in the body can be influenced markedly. Tritium is used as a target material in accelerators for production of

fast neutrons. It is also used as a radiation source in thickness gauges and is finding much commercial use in making luminous paints (Lambert and Vennart, 1972). It can be used to trace the movement of water in soils.

The absorption, and therefore the hazard, of tritium inhaled in air is much less when it is present as elemental tritium than as tritiated water, HTO. This is recognized in the maximum permissible concentration limits for a 40-hour work week, which are 5×10^{-6} μCi/cm^3 (5 μCi/m^3) for tritiated water and 2×10^{-3} μCi/cm^3 (2000 μCi/m^3) for molecular or gaseous tritium in air. The oxidation of tritium gas in air is usually slow, less than one percent per day, unless burning occurs. Tritium penetrates the skin, lungs, and gastrointestinal tract, either as tritiated water or in the gaseous form. As gaseous hydrogen, tritium is not significantly absorbed into the body and does not exchange significantly with the hydrogen in body compounds. As water the tritium entering the lungs or gastrointestinal tract is completely absorbed, and is rapidly dispersed throughout the body. Radiological control requires periodic biological monitoring of workers through measurements of tritium in urine (Lambert and Vennart, 1972).

As soon as a probable acute exposure is recognized, the individual should void his urine as completely as possible. The first sample must be saved as a control against the possibility of previous unrecognized exposures. The next, and subsequent voidings, are used to measure the tritium excretion. A rough rule of thumb, based on the peak urine concentration after a single acute exposure, is that 1 μCi/l of tritium in urine is indicative of a total integrated whole-body dose of about 10 mrem in the average person, if no treatment is instituted. Tritium exposures are comparable in their biological effect to whole-body exposure to external x or gamma radiations.

Tritium contamination of surfaces, including skin, cannot be measured except by special survey instruments because of the low energy of the beta particles. A special survey instrument has been developed to estimate the amount of tritium deposited in the body based on measurements made over the skin, such as the forearm (Powell *et al.*, 1977). While these data are less accurate and less sensitive than the urine assay, this monitor system may be useful as an early indicator of tritium exposure. Counting of surface smears in a gas-flow proportional counter is the usual method for detecting surface contamination. Air concentrations can be detected by air ionization chambers called "sniffers". The HTO content of air can be sampled by absorbing or freezing out the water. The residue is then measured in a liquid scintillation counter. Techniques for measuring tritium are described in NCRP Report No. 47 (NCRP, 1976).

Health effects in man have not been reported from single acute

exposures to tritium. There have been many instances of single exposure that were treated by forcing fluids as soon as possible. This has the dual value of diluting the tritium and physiologically increasing its excretion. Five instances have been reported of repeated exposures over periods of one to seven years to multicurie doses of tritium during preparation of batches of tritiated luminous compounds (Seelentag, 1973; Minder, 1969). Urine concentrations of tritium varied from 0.1 to 40 times the maximum permissible values throughout the periods of exposure according to the limited data that are available. The two men working most closely with the chemical preparation developed symptoms of nausea, lassitude and exhaustion, and a progressive anemia combined with a poorly defined physical deterioration that ended with aplastic panmyelocytopenia and death. A clear statement in these cases is difficult because both men at one time or another had worked with other radionuclides, received medication such as steroids, antibiotics, and transfusions, or worked in a manufacturing process involving polymeric plastics and organic solvents.

Between batches and when taken off the job, each man showed two- or three-component exponential decreases of tritium concentration in the urine with time. Tissue samples from the two men that died had specific activities of tritium bound to dried tissues (presumably organically-bound tritium) that were six to twelve times higher than concentrations in the urine samples. Thus, some of the tritium is incorporated into cellular components and has a turnover rate of several hundred days (Moghissi *et al.*, 1971; 1972). This long-term component, however, contributes only about 2 percent of the total dose (Snyder *et al.*, 1968).

The biologic half-time is about 10 to 12 days. Forcing fluids to tolerance, at least 3 to 4 liters per day, will reduce the half-time to about ⅓ to ½ of the normal value (Section 7.3.3.5). The dose is reduced proportionately to the effective half-life. Daily urine samples analyzed for tritium can be used to judge the effectiveness of the treatment by calculating the resultant effective half-life.

6.18 Uranium

Uranium, (V), element number 92, occurs only in radioactive form. Natural uranium (U-nat) is a mixture of ^{238}U, (~99.3 percent), ^{235}U (~0.7 percent), and ^{234}U (~0.006 percent). Uranium-238 is the head of the uranium/radium series and ^{235}U starts the uranium/actinium series. Uranium isotopes are also found in other series of transuranic

elements. The isotopes of U-nat have extremely long physical half-lives: 4.5×10^9 years for ^{238}U, 7.1×10^8 for ^{235}U, and 2.5×10^5 years for ^{234}U. U-nat and its daughter products emit alpha, beta, and gamma radiations.

Each of the three isotopes of U-nat also undergoes spontaneous fission at low rates. These are well below criticality even with the pure metal, but evidence of fission is found in the emission of fast fission neutrons and the presence of fission product isotopes. The daughter elements include two noble gases, radon-222 and radon-219; a third, radon-218, occurs in very low frequency and has no biological significance. These gaseous radionuclides are released in uranium and other mines and decay then to alpha- and beta-emitting isotopes of polonium, bismuth, thallium, astatine, and lead. The radon and the radon daughters adhere to atmospheric dust particles and constitute a serious inhalation hazard.

Most exposures to uranium and its daughters have occurred during the mining, processing, and fabrication of uranium into fuel elements for nuclear reactors or weapons. During this process, the uranium exists in several different physical states and chemical compounds. Raw ores contain from 0.1 percent to 1.0 percent uranium, chiefly U_3O_8. During the milling operation, the ore is concentrated, leached, and processed to ammonium diuranate and U_3O_8, a mixture called "yellowcake". The oxide is converted to UF_6 by fluorination and then processed through a gaseous diffusion plant, where the ^{235}U content is enriched to the required level for use as fuel elements for nuclear reactors. Enrichment to above 90 percent is possible for use in research and experimental reactors or nuclear weapons. The enriched UF_6 is converted to UO_2 and formed into pellets for manufacture of fuel elements. Standard metallurgical processing converts the oxide into the dense, silvery white, uranium metal. When fuel is reprocessed the uranium is dissolved in nitric acid, the fission products and transuranium elements are removed, and the uranium then is reprocessed to UF_6 for recycling.

Explosion and fire are the hazards associated with the handling of uranium. At room temperature, finely divided uranium metal may ignite spontaneously in air, oxygen, and even water (Wilkinson, 1962). The rapid oxidation of uranium under suitable conditions may cause a chemical explosion. The lower explosive limit for suspended uranium metal dust is 55 mg/l (Gindler, 1973).

A practical classification of the various uranium compounds is useful because differences in their absorption, transport within the body, deposition, and excretion affect their toxicity. Three levels of biologic mobility, or "transportability", for inhaled uranium have been devel-

oped (Scott, 1973). This term refers to the rate at which inhaled materials leave the lung without regard for the route of the movement. It is determined primarily by solubility but is also influenced by particle size. Highly transportable compounds take from weeks to months; moderately transportable, months; and slightly transportable from months to years. Table 6.2 lists this classification of uranium compounds.

In addition to transportability, the isotopic composition of the uranium must be considered in determining the hazard from different radiation properties. In uranium compounds enriched in ^{235}U to less than 5 to 8 weight percent and not irradiated in a reactor, the chemical toxicity is probably the limiting factor (Ford, 1964). In uranium enriched in ^{235}U to more than 8 weight percent or after irradiation, the radiation hazard predominates.

Uranium thus is considered either a chemical or radiologic hazard depending on its isotopic composition and its radiation history. With U-nat, the total quantity of metal absorbed is the determinant regardless of the compounds involved. One to five percent of an oral dose is absorbed and most is excreted by the kidneys (Hursh and Spoor, 1973). In acute or sub-acute poisonings, the kidney is the first organ to show chemical damage in the form of nephritis and proteinuria. Renal damage by U(VI) ion is produced by concentrations of the order of 0.1 mg/kg body weight. Uranium absorbed into the systemic circulation is eliminated principally via urine, about 60 percent of U(VI) and 20 percent of U(IV) within the first 24 hours. Fixation in the skeleton also occurs rapidly with about 8 percent of uranyl salts [U(VI)], but less than 1 percent of uranous salts [(U(IV)], being retained in the bone (Simon, 1972). Since soluble uranium is eliminated so rapidly from the body, only a urine sample collected during or immediately after exposure provides a reliable index of the extent of the exposure.

The critical organ for less soluble compounds of uranium, especially when enriched with ^{235}U and ^{234}U, is likely to be the bone, or when

TABLE 6.2—*Classification of uranium compounds according to transportability from the lung after inhalation (Scott, 1973)*

Highly transportable (weeks to months)	Moderately transportable (months)	Slightly transportable (months to years)
UF_6	UO_2	UO_2
UO_3	U_3O_8	U_3O_8
$UO_2(NO_3)_2$	UO_3	Uranium oxides
UF_4	UF_4	Uranium hydrides
Uranium sulfates	Uranium nitrates	Uranium carbides
Uranium carbonates		Salvage ash

inhaled, the lung. The biological half-time is usually considered to be 300 days for the bone, 100 days for the whole body, and 15 days for the kidney (ICRP, 1960). In cases of ingestion, the slightly transportable compounds, the oxides and carbides, are eliminated principally via the feces. After inhalation, the retention depends on particle size and chemical form. Long biological half-times of 120 days or more can be anticipated from slightly transportable compounds having particle sizes under 2 micrometers. Although the nominal biological half-time for uranium in the lung is 120 days (ICRP, 1959), the uranium oxides have biological half-times of up to 1470 days (West and Scott, 1969).

Uranyl nitrate, uranyl fluoride, uranium pentachloride, uranium trioxide, sodium diuranate, and ammonium diuranate are absorbed through the skin of experimental animals. Several of these compounds also cause mild to moderate skin irritation. Contamination of the eyes can be a serious hazard since extensive absorption via the cornea occurs rapidly.

Exposures of about 0.1 mg/kg or more of soluble U-nat results in chemical injury of the cells of the lower portion of the proximal convoluted tubule of the kidney (Luessenhop *et al.*, 1958). There is usually a lag period of 6 hours to several days followed by necrosis (Yuile, 1973). Mild glomerular damage also develops with signs such as albuminuria, hematuria rarely, and hyaline and then granular casts in large numbers (Stone *et al.*, 1961). Urinary catalase is usually elevated. Other renal function tests, especially those that measure tubular excretory capacity, may be abnormal and azotemia may occur after a severe exposure. However, even after exposure to levels that cause necrosis, the kidney shows evidence of regeneration within 2 to 3 days, depending on the severity of the initial injury. The injured kidney, upon recovery, usually shows evidence of a tolerance to subsequent exposures at the same or higher levels. This tolerance does not develop unless the kidney has been sufficiently injured to require regeneration of tubular epithelium.

A number of the reported accidental exposures to soluble uranium compounds have been reviewed by Hursh and Spoor (1973). Most of the exposures were by inhalation of UF_6 that leaked from enclosed systems. One accident (Howland, 1953) resulted in the death of two employees and serious injury to three others. The deaths and injuries were caused by the hydrofluoric acid that was released when steam reacted with UF_6; this reaction accounts for the highly corrosive features of the exposure. In another accident (Boback and Heatherton, 1966), an employee inhaled 13 mg of uranium as UF_6 but recovered after several days' hospitalization; he showed evidence of only transient kidney damage.

In view of extensive industrial experience, it appears that natural uranium is less toxic to man than was expected on the basis of animal experiments. There has been no evidence of chronic chemical toxicity after years of exposure to low levels (Scott *et al.*, 1970).

Because of the rapid excretion of soluble uranium compounds, the primary value of routine urinalyses for uranium is to provide a general guide as to the effectiveness of exposure control in a group of workers in a specific area of a plant. A guide to the various types of samples and where and when they should be collected has been published (Scott, 1973).

When a single large exposure has occurred, continuous measurement of the urinary excretion of uranium is recommended, especially when the solubility of the compound is known or can be estimated. *In vivo* counting of the 186 keV gamma from ^{235}U, however, is superior to urinalyses in evaluating body burdens and is the best method available to assess the inhalation of insoluble material. Care must be taken when evaluating exposures to uranium enriched in its content of ^{235}U because the ^{234}U content is also increased. When the enrichment is above a few percent, much of the radiation comes from ^{234}U because of its shorter half-life and higher specific activity. It is necessary to determine the percent ^{234}U and the specific activity of the material because the ^{234}U content varies with its processing history (Scott, 1973).

Treatment with sodium bicarbonate produces a uranyl bicarbonate complex in tubular urine that is less nephrotoxic; it also promotes migration to extracellular fluids and deposition in the bone. Oral doses or infusions of sodium bicarbonate are regulated so as to keep the urine alkaline as determined by frequent pH measurements. Use of a diuretic drug (Section 7.3.4.4) has been advocated (ICRP, 1978). If the chemical toxicity becomes severe enough, renal dialysis would presumably be useful since the damage of the proximal convoluted tubule is temporary and recovery is fairly rapid.

Both EDTA and DTPA have been used in experimental animals (Catsch, 1964) to increase excretion. DTPA increased the LD_{50} in mice injected intraperitoneally with uranyl nitrate in doses of 6.7 mg U/kg to 16.2 mg U/kg (Catsch, 1959). The effectiveness of both chelating drugs is strongly time dependent and no protective action is observed with a delay of 4 hours or more after exposure (Catsch and Harmuth-Hoene, 1979).

7. Therapy Procedures and Drugs

7.1 Skin Decontamination

7.1.1 *Objectives*

The objectives of skin decontamination are to remove as much of the radionuclide as practicable in order to reduce the surface dose rate and to prevent activity from entering the body. Careful skin decontamination can also enhance the accuracy of whole-body counting for estimation of internal body burdens. An over-aggressive skin decontamination effort must be avoided since it may injure the natural barriers in the skin and so increase percutaneous absorption.

7.1.2 *Physical and Biological Principles*

Many cases of skin contamination with radioactive materials will be decontaminated by nonmedical personnel at or near the accident scene. When initial cleansing methods are not effective, the patient should be referred to a physician. The physician's decisions on decontamination procedures should be based on an understanding of the special physical and biologic principles involved. Success in achieving the objectives stated above requires thoughtful appraisal of the level of residual contamination, rate of successful decontamination, and condition of the skin. These factors change continuously as the cleansing procedures proceed.

The full thickness of the skin is about 2 mm. Of this, the epidermis has a depth of about 0.1 mm in most parts of the body. On the palms and palmar surfaces of the fingers it may reach 0.8 mm and on the sole and toes of the foot, 1.4 mm, due to the thickened stratum corneum (Laylee, 1964). For the estimation of dose to the skin, the relevant tissue is the basal cell layer which is located at an average depth of about 0.07 mm except on the palms and soles as noted above. On the face the depth of the basal cell layer is somewhat less than in the rest of the skin. The small blood vessels of the dermis can be injured when energetic beta, x, or gamma rays impinge on the skin in high doses—several hundred rads or more.

The possibility of biologic effect from skin contamination varies with different types of radiation and their energies. With alpha radiation, the horny layer or stratum corneum effectively shields the basal layer. For example, plutonium alpha rays with a range of only about 0.04 mm in soft tissue do not reach the basal cell layer of the epidermis. Contamination with alpha emitters is of concern, however, because of the possibility of percutaneous absorption and possible irradiation by beta or gamma emission from daughter products. Loose contamination with alpha emitters on skin may also result in an ingestion and inhalation hazard.

One millimeter of tissue will reduce most beta radiations by a factor of 2 or more so the dose from surface beta contamination to the subcutaneous tissue is much less than to the epidermis. Beta radiation with energy less than 50 keV does not penetrate the outer layer of the skin and even at energies up to 200-300 keV, much attenuation occurs (Johns, 1964). The dose rate at the basal layer from 1 μCi of ^{14}C, average beta energy of 50 keV, uniformly distributed over 1 cm^2, is 1.7 rad/hour, while for the same amount of ^{32}P, average beta energy of 695 keV, it is 6.4 rad/hour (Newberry, 1964). The surface activity of beta emitters required to produce acute skin damage is thus highly variable. An acute irradiation of the skin at high dose rates (30+ rads/min) with 200 kVp x rays produces erythema at about 600 rads and moist desquamation at about 2000 rads (NAS/NRC, 1967).

Low-energy gamma radiation (10–15 keV) has an effect on the skin similar to beta particles. Gamma radiation of 50-300 keV from a source on the skin is capable of producing biologic effects in the deeper layers of the skin and in the subcutaneous tissue.

Percutaneous absorption is of concern with all types of radionuclides and, when it occurs, most chemicals pass through the epidermis rather than its sweat glands and hair follicles (Tregear, 1961). The most important barrier to penetration is the horny layer, which has been described as a "hydratable fibre mat" rather than a set of membranes (Tregear, 1964). When contamination reaches the bottom of this layer it diffuses rapidly through the rest of the epidermis and into the capillaries of the dermal papillae. The lower layers of the stratum corneum possess a sponge-like capacity to fill and empty (Tregear, 1964). This process may explain why alpha contamination can sometimes "reappear" after decontamination (Lawson, 1964). The level of residual alpha contamination on the surface of the skin may therefore increase 24-48 hours after initial satisfactory decontamination.

Percutaneous absorption is a passive process determined by the chemical and physical properties of the contaminating substance and its interaction with the epidermis (Allen, 1967). The range of permea-

bilities of different substances is large (0.0007 to 1100 nm/sec). Most aqueous solvents are in the range of 0.5 to 10 nm/s while most nonaqueous materials are in the range of 0.02 to 1.7 nm/s (Healy, 1971; Tregear, 1966). Mechanical damage and hydration increase absorption while acid burns tend to decrease absorption (Blank and Scheuplein, 1964). Dilute acid burns facilitate absorption, at least this is true of plutonium (Oakley and Thompson, 1956). Since each compound will have a different rate of percutaneous absorption, generalizations are of little help. For example, a 10 percent aqueous solution of $^{89}SrCl_2$ applied to human skin is rapidly absorbed (Loeffler and Thomas, 1950; Loeffler *et al.*, 1951), while less than 0.3 percent of an aqueous solution of potassium iodide (^{131}I) is absorbed. The absorption of plutonium in 0.4N HNO_3 applied to the skin of the palm of the hand was less than 0.0002 percent/hour (Langham, 1959). When internal contamination is a major concern, e.g., ^{239}Pu, it must be assumed that percutaneous absorption can occur and therefore the integrity of the horny layer barrier should not be breached.

Contaminants may be held to the surface of the skin by electrostatic forces or surface tension. Also, chemical compounds may be formed between the contaminant and skin protein. Mechanical entrapment in the hexagonal plates of the horny layer may occur with material of small particle size (Lincoln, 1963). Although contamination may sometimes be extremely difficult to remove by physical or chemical means, the skin will cleanse itself, the horny layer being shed and renewed on a 12-15 day cycle (Baker and Kligman, 1967). The turnover rate differs considerably in various areas of skin. Forehead skin appears to turn over faster while on the back of the hand it is slower than for other parts of the body (Weinstein and Van Scott, 1965). Any damaging influence such as ultraviolet light, stripping with sticky tapes, or scrubbing reduces the renewal time. In general, most contamination is limited to the upper part of the horny layer and will therefore usually be shed in just a few days.

7.1.3 *Evaluation of Contamination*

After an accident has occurred, the initial radiation survey of the skin should be made with both a beta-gamma and an alpha monitoring instrument. See Sections 3.4.2, 4.1.1, and 4.1.2.

Skin contamination with beta emitters of even moderate energy can sometimes be missed by a person inexperienced in the proper use of radiation monitoring equipment such as a field survey instrument. Start surveys with an open shield so that both beta and gamma will be detected. Beta emitters are capable of producing beta burns if heavy

contamination occurs and if the contaminated person, unaware of its presence, allows it to remain on the skin or surgical glove too long.

Another method for determining the distribution of radioactive material on skin is the high speed alpha-autoradiography technique in which the contaminated area is placed against a zinc sulfide scintillation screen and Polaroid film for a few minutes exposure time (Hsieh *et al.*, 1965; Matsuoka *et al.*, 1968). The time of exposure needed for best visualization depends on the level of contamination and may take some experimentation.

7.1.4 *Decision Levels*

The physician will want to know when the decontamination effort can be safely stopped and also when it is unwise to continue. Citing an absolute numerical level would require so many assumptions as to be misleading. Typical questions that arise are: Is the contamination confined only to the superficial parts of the horny layer? Has it penetrated uniformly throughout the layer, or has it already penetrated through to the basal layer? If the contamination is on or near the surface, it will probably be sloughed in two or three days. If it is uniformly distributed throughout the horny layer, the rate of sloughing will be similar to the turnover time of the horny layer itself, about 6 to 7 percent per day. The rate of the initial contamination, at least as far as absorption is concerned, depends on its physical and chemical characteristics. For these reasons, it is not realistic to set down arbitrary radiation levels that would indicate whether or not to pursue additional decontamination.

Nevertheless, calculations have been made to estimate the contamination level of various radionuclides on the skin that would deliver 15 rem/year to the basal layer if maintained 40 hour/week and 50 week/year (Healy, 1971). Such a case is only theoretical since contamination would remain only days to a few weeks even without interim decontamination. It does, however, help reassure the physician when he recognizes, for example, that 0.8 nCi/cm^2 of ^{32}P could be left on the skin without exceeding the occupational dose rate of 15 rem/year to the basal layer. Such a quantity represents about 1800 disintegrations/minute. Since many GM systems are 10 percent efficient, a rough rule of thumb can be used to convert d/min beta to counts/min, i.e., d/min $\div$ 10 = c/min. In the example above, a persistent level of almost 180 c/min could be left on the skin and would not exceed the 15 rem/year dose level to the basal layer. Levels twice as high on the forearms and five times as high on the hands will deliver doses at the current

"permissible" levels (NCRP, 1971). It has been suggested that 10^{-4} μCi/cm^2 beta and 10^{-5} μCi/cm^2 alpha could reasonably be considered as maximum permissible levels of skin contamination (Dunster, 1962).

As a practical matter, working numbers used by some health physicists as upper limits on skin contamination that is especially difficult to clean are 1 mR/h beta (portable GM meter) and 1000 dis/min alpha (air proportional counter with a 60 cm^2 window). Much higher levels may be encountered in emergencies and the decision to cease decontamination will probably rest on evidence of the decreasing effectiveness of the decontamination efforts and/or presence of signs of excessive irritation to the skin. With reference to skin irritation, it should be recognized that signs of excessive decontamination effort will be more evident 24 hours later than at the time the decontamination is going on. If high levels of activity remain on the skin, it will probably be prudent to resort to mild decontamination efforts 2 or 3 times per day rather than to a single intensive effort.

The above discussion should not be interpreted as encouragement for a cavalier attitude toward skin contamination. It is always wise to remove as much as possible without seriously irritating the skin. Most workers will be apprehensive if they can see a positive instrument reading. Saying that such a count rate is inconsequential and decontamination is not needed will not satisfy most patients. After a reasonable effort has been made, it is much easier to convince the patient that further efforts are not necessary and might be counterproductive.

7.1.5 *General Principles of Decontamination*

Soaps and detergents emulsify and dissolve contamination and are frequently all that are needed for decontamination of skin. Gentle brushing or the use of an abrasive soap or abrasive granules[2] dislodges some contamination physically held by the skin protein or removes a portion of the horny layer of the skin. Addition of a chelating agent helps by binding the contaminant in a complex as it is freed from the skin.[3] Sodium hypochlorite (household bleach) has been found useful for several plutonium compounds. It can be used at full strength (~5 percent sodium hypochlorite) on all but the head and neck where a 1:5 dilution with water is advisable. It does make plutonium insoluble and this could be a disadvantage. An acid soap used with an aqueous solution of DTPA has been used successfully (Ducousso *et al.*, 1972).

[2] Mixture of 50 percent powdered detergent and 50 percent corn meal.

[3] Mixture of carboxymethyl cellulose, 3 percent powdered detergent, 1 percent CaEDTA and 88 percent water homogenized into a cream.

Titanium dioxide[4] has an abrasive action and should not be used near the face or sensitive areas.

If long-lived alpha emitters are the contaminants, contaminated hair should be removed by clippers or an electric razor. The eyebrows should be clipped only if further removal of contamination is deemed essential. The eyebrows regrow slowly and may take six to eight months for return to normal. Hair clippings should be collected in a plastic pouch and surveyed for contamination. When hairy areas have been contaminated with beta-gamma emitters and absorption through nicks, cuts, or scrapes is of less concern, shaving with safety razor and soap will often remove most of the contamination.

While chemical techniques are seldom necessary, they can be used. Potassium permanganate,[5] a powerful oxidizing agent, and sodium acid sulfite, which removes the permanganate stain, will remove a portion of the horny layer. In especially stubborn cases where the contamination seems to be localized in one or two tiny spots in the thick horny layer, such as the palms of the hands, a high-speed abrasive wheel can be used to sand off the spot. Obviously care must be taken to prevent environmental contamination. Sticky tapes have been used successfully, but they tend to remove the horny layer rapidly and, if not used carefully, can lead to increased percutaneous absorption (Tregear, 1966). A table of decontamination techniques with detailed instructions is available (BRH, 1970).

When using any of the above agents or techniques, always begin with the least irritating and proceed to stronger or more abrasive techniques only if absolutely necessary. It should be recognized in this sequence that the stronger agents are used after a certain amount of skin irritation has already occurred. It is a common mistake to underestimate the potential for skin irritation until too late. Particular care should be taken on the more sensitive and thin skin areas, such as an area that has been skin grafted or used as a donor site. Check the progress by frequent resurveys with the radiation detection instrument. If long-lived alpha contamination is left on the skin to be shed by the normal renewal process, it should be covered with a dressing. Rubber gloves are particularly useful for this when the hands are contaminated. Each day when the covering is removed, both it and the skin should be monitored for the amount shed and the residual contamination which remains.

[4] Precipitated titanium dioxide rubbed up with a small amount of lanolin into a thick slurry.

[5] Saturated solution of $KMnO_4$ in 0.2 N sulfuric acid. Pour over wet hands with gentle rubbing, then rinse. Apply freshly prepared 5 percent solution of $NaHSO_3$ to remove stain and then rinse immediately.

7.2 Treatment of Contaminated Wounds

After emergency first aid has been administered to control hemorrhage and treat shock, the crucial first step in decontaminating wounds is to find the contamination. With energetic beta emitters and most gamma emitters this is not a major problem but with weak beta and alpha emitters the detection can be difficult. In most cases the removal of contamination, once found, presents no special surgical challenge but it does require considerable patience and perseverance.

7.2.1 *Translocation and Absorption*

The translocation and absorption of a contaminant from a wound to the general circulation or to regional lymph nodes is the major concern. The physicochemical characteristics, e.g., solubility, pH, tissue reactivity, and particle size, will determine the speed of movement from the wound. If the contaminant is in a highly acidic or caustic state, the tissue proteins may coagulate and reduce dispersion into the tissue fluids. Some radionuclide compounds will gradually change their solubility after prolonged contact with body fluids (Saenger, 1968). Plutonium chloride or nitrate is soluble in an acid pH, but in the slightly alkaline biologic milieu it transforms into hydroxides that polymerize into nontransferable aggregates. Plutonium oxides, especially those that have been high-fired, are considered rigorously insoluble, yet after prolonged exposure to body fluids they become partially soluble (transportable). In general, long-lived radionuclides such as ^{239}Pu and ^{90}Sr are of greatest concern because they continue to irradiate the surrounding cells intensely at the wound site or in the internal organs, if translocated.

In experiments on beagles, particles of high-fired PuO_2 (geometric mean diameter, 0.7 μm) that had been implanted as a simulated wound, were detected in the regional lymph nodes within a few minutes to one or two hours after exposure with concentrations reaching a maximum of about 60 percent of the implanted dose after 30-40 days (Bistline *et al.*, 1972). Translocation of air-oxidized plutonium was slower, being 3 percent at 14 days and 17 percent at one year (Watters and Lebel, 1972). This slower movement may have been due to larger particle size. Plutonium nitrate implanted in the dog's paw built up rapidly in the superficial lymph node, concentrations reaching a maximum in ten days.

These dog experiments indicate that insoluble PuO_2 in the form of small particles can be rapidly translocated. Thus, prevention of movement of even an insoluble compound requires prompt action.

7.2.2 *Classification of Wounds*

7.2.2.1 *Abrasions.* A contaminated abrasion presents considerable potential for absorption since the surface is often raw and bleeding, and the epidermal barrier is no longer intact. Usually such surfaces can be cleaned with a detergent and, if necessary, a topical anesthetic, such as 4 percent lidocaine, can be used to allow more vigorous cleansing. After a reasonable effort, there is no need to attempt to remove all contamination since the residue that remains on the surface will probably be incorporated in the scab. When the scab sloughs it should be saved for measurement of radioactivity and proper disposal.

7.2.2.2 *Punctures.* Punctures may result from contaminated metal or glass slivers, small tools, or accidentally by hypodermic needles broken during injection. In explosions a small missile may be driven through the skin and may leave only a small entry wound. Its exact position may be difficult to locate and thus require considerable surgical extension of the wound.

7.2.2.3 *Lacerations.* A simple clean laceration made superficially by a contaminated sharp object is probably the least difficult type of wound in which contamination has to be detected and then decontaminated. Often much of the contamination is deposited on the lips of the wound. When lacerations are ragged and deep, contamination may be deposited in fascial planes with subsequent migration that makes difficult the detection of the contamination and subsequent decontamination. There is also the possibility of direct entry of contamination into a blood vessel or major lymph channel.

7.2.3 *The Fate and Tissue Reaction of Unremoved Contaminants*

As mentioned above, soluble compounds are often rapidly absorbed and enter the metabolic pathways characteristic of the particular element and its compound. Insoluble compounds, especially if they are fine particulates, migrate along lymph channels to the regional lymph nodes. The regional node often is only a partial and temporary block in which case the contaminant moves on to the thoracic duct and enters the general circulation (Gomez *et al.*, 1972). For this reason, excision of a regional lymph node is seldom a definitive step in decontamination. It could be done, however, when monitoring reveals a large concentration in the regional node.

Depending on the type and amount of radiation emitted by the contaminating material, tissue reaction to intense local irradiation may occur and may influence migration of the contaminant. Plutonium allowed to remain subcutaneously for several years has been reported

to result in a fibrous nodule not unlike a foreign body reaction (Lushbaugh *et al.*, 1967). In one case the alpha radiation dose to the surrounding cells from a 5 nCi subcutaneous deposit of plutonium was estimated to be over 75,000,000 rads and the resultant nodule showed severe cellular changes in the basal area of the epidermis cytologically similar to precancerous changes (Lushbaugh and Langham, 1962). In a long-term follow-up study of workers exposed to plutonium, one individual with a deposit of about 5 nCi in a finger for 27 years showed no clinical evidence of skin changes or subcutaneous nodule formation (Hempelmann *et al.*, 1973). It has been suggested that the depth of deposition in relationship to the basal epithelial layer of the skin may be related to nodule formation (Voelz, 1975).

It is extremely important to check all wounds for contamination when skin contamination has been detected. When mixtures of alpha, beta, and gamma emitting contaminants are possible, the alpha emitting contamination may be overlooked rather easily because of the ease with which the beta-gamma emitting contamination is detected. It is also necessary to consider the possible chemical hazards of the compounds along with the radioactive contaminants, as well as bacterial or other microbiological contamination.

7.2.4 *Precautions*

Beta-gamma emitting contaminants in large quantities may present a radiation hazard to physicians, nurses, and other attendants. The potential exposure situation can always be evaluated rapidly with portable beta-gamma survey instruments. Improvised shielding may be necessary if a special shielded decontamination facility is not available. In order to estimate the skin exposure on the hands of the surgeon, thermoluminescent dosimeters can be taped at a location on the palmar side of the hand that will not interfere with tactile sensation or grip. If the contaminant is a weak beta emitter such as ^{3}H or ^{14}C, double gloves should provide sufficient protection.

7.2.5 *Treatment of Wounds and Surgical Considerations*

When it is determined that the patient has radioactive material in a wound, efforts to clean the wound should begin in a manner similar to cleaning a dirt-laden wound or removing a foreign body. Irrigation of the wound with sterile water or saline, free bleeding, and occluding venous return with a tourniquet have been advocated for immediate action (Norwood, 1962b).

If the patient's general condition requires first-aid procedures or medical therapy for serious complications, they shall take precedence over the decontamination effort. Another early consideration of importance is determination of the possible advantages of administering blocking agents and/or the use of isotopic dilution (see Section 7.3.3). If the contaminant is plutonium or one of the other long-lived alpha emitters for which DTPA is an effective chelating agent, treatment should be started promptly (see Section 7.3.5.3).

After administering suitable drug therapy as indicated, further decontamination and surgery may be considered. Thorough irrigation with normal saline will often flush out much of the contaminating material. A pulsating water jet lavage has been used with some additional success (Grower and Bhaskar, 1972). The wound frequently needs to be enlarged for better irrigation and it may be necessary to excise a block of tissue in order to remove most of the contamination. Enlarging the wound with an incision on each side and under the wound and then lifting out the block of tissue is often effective. If the initial laceration was jagged or there was much tissue destruction, this technique may provide a wound that is easier to close. Use of a skin biopsy punch is a convenient way to excise small puncture wounds. Serious attention should be given to the cosmetic outcome of surgical decontamination especially if the face is involved. As surgical instruments become contaminated, as determined by frequent monitoring, they should be removed from the surgical field and replaced with fresh, sterile tools in order to prevent extension of contamination. The difficulties involved in detecting the contaminant, while preventing its spread, will mean that the surgical procedure may last much longer than normally expected. Many more instruments and sponges than usual will be required. Even though pulmonary contamination has occurred, inhalation anesthesia and respiratory assistance apparatus should be used without regard to possible risks of contaminating the equipment. Only those portions of the equipment directly in contact with the mucous membrane of the respiratory tract are exposed to a significant risk of contamination (Ducousso *et al*, 1972). Each apparatus should be monitored carefully for residual radioactivity before removal from the decontamination area and before use with other persons.

There is no reason to leave a wound open unless closure has been so long delayed that infection is likely. When drains are used, dressings should be monitored for radioactivity. Care should be used to collect any scab when it detaches from the wound. Often appreciable contamination can be found in it when it is analyzed (Ducousso *et al*, 1972).

Since any debridement involves some risk of promoting the translocation and absorption of the contaminant, the surgical procedures

for removal of long-lived alpha emitters, such as plutonium or americium, should be performed while, or after, DTPA is given systemically (Ducousso *et al.*, 1972; Smith, 1972). DTPA solution can also be used as an irrigation fluid. Any burning sensation caused by CaDTPA or CaEDTA when used for wound irrigation can be prevented by flushing the wound with 2 percent lidocaine. An effective irrigating solution consists of one gram CaDTPA and 10 ml of 2 percent lidocaine in 100 ml 5 percent glucose solution or isotonic saline. Even though there may be increased absorption from the wound due to chelation at the site of deposition, the plutonium is bound to the chelating agent and is excreted without entering the metabolic pool (Lafuma *et al*, 1968). Schofield (1969) prefers to use CaDTPA intravenously rather than by irrigation as soon as possible after a contaminated wound has occurred. CaDTPA also appears to be useful in treating wounds contaminated with transuranium elements other than plutonium (Volf, 1971).

In all cases of contaminated wounds, urine and fecal bioassay and/or *in vivo* body counting should be used to estimate the uptake of the contaminant into the body. All removed tissue, gauze sponges, and irrigation water should be retained for radiochemical analysis. Since it is seldom possible to remove all contamination during the initial decontamination effort, dressings should be monitored for contamination.

When small amounts of contamination remain in the wound, the site should be monitored periodically in order to document translocation. An inspection of the wound every year is advisable to detect nodule formation. If found, excision and radiochemical and pathology studies on the nodule are recommended.

7.2.6 *The Decision to Amputate*

When an extremity is severely contaminated and adequate decontamination is not possible, the surgeon may be faced with the decision whether or not to amputate. The general basis for treatment decisions have been covered in Section 5. More specifically, the conservative approach may be stated as follows: Unless the extremity is so severely injured that functional recovery is unlikely, or unless the beta-gamma contamination is so severe that extensive and severe radiation-induced necrosis can be expected, amputation is rarely indicated. Long-lived alpha emitters such as plutonium may represent a potential long-range threat, but conservative treatment should be tried first and the decision to amputate postponed until the potential long-term risks are clearly defined and understood. In other words, *decontaminate but do not mutilate*. Adequate DTPA treatment reduces significantly the amount

of plutonium translocated from the wound to bone or liver, and permits more time for careful evaluation and consultation. Even though amputation is rarely required, aggressive debridement and surgical decontamination is desirable and useful, and can usually be accomplished without endangering a functional recovery.

7.3 Treatment of Internal Contamination

7.3.1 *Introduction*

The procedures for treatment of persons with internally-deposited radionuclides are intended to reduce the absorbed radiation dose and hence the risk of possible future biological effects. These aims can be accomplished by the use of two general processes: (1) reduction of absorption and internal deposition; and (2) enhanced elimination or excretion of absorbed nuclides. Both are most effective when begun at the earliest possible time after exposure.

Treatment is most effective if absorption of contaminants into the systemic circulation (7.3.2) is prevented. Administration of diluting and blocking agents (7.3.3) may also enhance elimination rates of the radionuclide or reduce the quantity of radionuclide incorporated in tissue. Therapeutic measures that use mobilizing agents (7.3.4) or complexing drugs (7.3.5) are less effective when the radionuclide has already entered the cells of target tissues and organs. The most important considerations in treatment are: (1) selection of the proper drug for the particular radionuclide; and (2) timely administration after exposure.

General guidance concerning factors involved in determining the necessity of treatment is given in Section 5. There is no numerical exposure value that can be used as an absolute guide for this determination. For relatively risk-free procedures, the need for rapid action will probably preempt the desire to make a more careful evaluation of the exposure. In any event, treatment should be started immediately when the probable exposure is judged to be significant.

The cessation of treatment is another decision that depends on the experience and judgment of the physician-in-charge. This decision rests on the relative risks versus the effectiveness of the particular treatment and will be raised primarily with relation to continuation of the use of mobilizing or chelating agents. These treatments may be of sufficient duration that a judgment of their current therapeutic effectiveness can be based on measurements of the urinary excretion rate

of the radionuclide with and without treatment, or possibly on the effective half-life of the radionuclide determined by whole-body counting data. This decision is not as crucial as that relating to initiation of treatment and can be made after due deliberation that includes consultations as desired.

The tables in the following sections present selected generic drugs along with the usual dose instructions for other medical problems and explanatory or cautionary remarks. In cases of emergency and significant radiation exposure risks, higher drug doses with consequent higher risks of adverse drug reactions may be justified. The sparse literature on human therapy for incorporated radionuclides shows that cases warranting treatment have often received an aggressive course of therapy including the employment of agents and doses that are not usual for other medical problems. The decisions to follow this course have been based on the physician's judgment and on careful clinical management of the case. The drug schedules listed in this report are in the conventional dose ranges.

The drug listings are not intended to be exhaustive. The physician is cautioned to consult additional references regarding possible contraindications and restrictions in the use of these drugs since it is not possible to include all pharmacologic details in this report. A physician should feel free, however, to use any drug approved by the FDA for any use that he or she deems appropriate in his or her professional judgment. In a few instances this report includes investigational new drugs or compounds that have not been generally used for medicinal purposes. These items are presented for completeness of information.

7.3.2 *Procedures to Reduce Gastrointestinal Absorption*

7.3.2.1 *Introduction.* Gastrointestinal absorption of radioactive substances can be reduced either by washing out or by use of medications selected for specific elements. These medications combine with the radionuclide so that it becomes less available for absorption and is then eliminated in the stool. Examples of these are the alginates and aluminum-containing compounds that tightly bind radioactive strontium. Other substances act by exchange, e.g., resins that bind the radioisotope in place of another ion. The radioactive substance that has exchanged is subsequently eliminated in the feces. The following procedures can be used for reducing the gastrointestinal absorption of radioactive substances.

7.3.2.2 *Stomach-Lavage.* This procedure may be used for the evacuation of toxic materials from the stomach by means of a gastric tube.

It would generally be used in the highly unusual circumstances where known intake of a large quantity of radionuclides will offer a significant threat to present or future health and where intake has occurred recently enough so that the material is still in the stomach.

After insertion of a nasogastric or gastric tube, water is introduced into the stomach with a bulb syringe and the water is then siphoned back. This process is continued until the stomach washings are relatively free of radioactive material. The most effective position for this procedure is to position the suction tube near the pylorus with the person lying prone with his left side elevated to about 45°. It is best to have the patient in a head-low position to prevent aspiration. The washings should be saved for radioactivity measurements in the laboratory. If the procedure is unsuccessful for any reason, consider the use of emetic drugs (Section 7.3.2.3).

7.3.2.3 *Emetics.* (See Table 7.1) Emetics are compounds that are used to induce vomiting in order to empty the stomach promptly and completely after the ingestion of poisonous materials. In most instances stomach lavage would be the procedure of choice, but it may not always be successful. Emetics act by stimulating the gastric mucosa, by stimulating the vomiting center in the brain (medulla), or a combination of these two actions. Emetics are usually most effective when 200-300 ml of water are taken concomitantly. Their use is contraindicated if the state of consciousness is impaired, such as in states of shock or inebriation, and after the ingestion of corrosive agents or petroleum hydrocarbons.

TABLE 7.1—*Emetic drugs*

Compound	Route of Administration and Dose		Remarks
Apomorphine hydrochloride	*Subcutaneous*		Very unstable in the presence of light or air. If solution becomes emerald green, deterioration has occurred. May cause central nervous system depression. Do not repeat dosage.
	Adults	5–10 mg	
	Infants	1 mg	
Ipecac	*Oral*		Can be very irritating to mucous membranes. Dose may be repeated at 15 minute intervals until vomiting occurs. NOTE: TINCTURE OR SYRUP OF IPECAC IS NOT TO BE CONFUSED WITH THE FLUID EXTRACT WHICH IS 14 TIMES MORE POTENT. The fluid extract is no longer "officially" available.
	Capsule:	1–2 g	
	Syrup:	15 ml	
	Tincture:	5–20 ml	

The side effects of emetics include restlessness, tremors, persistent nausea, weakness, pallor, irregular and rapid respiration, tachycardia, decreased blood pressure, dizziness, fainting, and unconsciousness.

7.3.2.4 *Purgatives.* (See Table 7.2) Purgatives or laxatives are classified generally as irritants, bulk forming substances, lubricants, and wetting agents. Castor oil, cascara, and senna are examples of irritants. These release ricinoleic acid after lipolytic action in the small intestine; this compound stimulates intestinal contractions. Slower acting drugs, including bulk-forming laxatives and wetting agents, are not generally appropriate. Use of enemas or colonic irrigations may be valuable in reducing the residence time of radioactive materials in the colon.

Selection of a purgative should include the consideration of speed of action. Furthermore, it may have special properties by which the purgative itself may produce a less soluble compound of the involved radionuclide. Magnesium sulfate is an example of a saline cathartic that may produce relatively insoluble sulfates with some radionuclides and thus reduce absorption. The fact that magnesium sulfate has been used should be indicated to the radiochemist who will analyze the fecal sample since it introduces complications in the analytical procedure for certain radionuclides. Saline cathartics (see also Section 7.3.3.4) usually act within 3-6 hours. Action depends on the poor absorption of cations, anions or both. A hypertonic solution is produced in the intestine and water is attracted from the intestinal mucosa. These cathartics are especially useful in eliminating certain poisons from the gastrointestinal tract.

All laxatives are contraindicated in the presence of abdominal pain of undetermined etiology, ileus, or an acute surgical abdomen.

Adverse reactions may include dehydration, cardiac irregularities, enteritis, dyspnea, syncope, rash, and loss of electrolytes, especially of potassium, which can cause weakness.

7.3.2.5 *Ion Exchange Resins.* (See Table 7.3) The use of ion exchange resins has been largely limited to decreasing gastrointestinal uptake of ingested or inhaled radionuclides. Even this use has been limited mainly to experimental tests in animals. Experience in man is represented mainly by such "ion exchangers" as ferric ferrocyanide (Section 7.3.2.6) and alginates (Section 7.3.2.8).

The limited experimental studies on ion exchange resins show that they can be used to accelerate fecal excretion of ^{137}Cs if given orally shortly after ingestion of the radionuclide. Majle and Gorzkowski (1975) reduced the effective half-life of ^{137}Cs from 7 days to less than 2 days in rats by use of a cation exchange resin, Bio-Rex 40,[6] given 1.8 g twice daily starting immediately after exposure. It was also effective when employed 6 hours after contamination. Iinuma *et al.* (1971)

[6] Made by Bio-Rad, USA.

TABLE 7.2—*Purgative drugs*

Compound	Route of Administration and Dose	Remarks
Irritant Laxatives		
Bisacodyl	*Oral* Adults: 10–30 mg (5 mg/tablet) Child: 5 mg tablet *Rectal* Suppository 10 mg	Usually acts within 6 hours. Usually effective in 15–60 minutes.
Castor Oil	*Oral* Adults: 15–30 ml Child: 4 ml	Acts in 2 hours. Usual adult dose 15 ml.
Castor Oil, Emulsified	*Oral* Adults: 30–60 ml Child: 7.5–30 ml	
Phenolphthalein	*Oral* Adults: 60 mg As much as 200 mg has been given.	Acts in 4–8 hours. Action may persist for 3–4 days because small amounts are absorbed and circulate through the enterohepatic system. Some persons are hypersensitive.
Saline Cathartics		
Magnesium sulfate	*Oral* Adults: 15 g (powder)	Dissolve in a glass of ice water. Magnesium salts should not be used in the presence of renal insufficiency since small amounts can be absorbed and these are not readily excreted. The retained magnesium exerts a depressant effect on the central nervous system.
Magnesium citrate solution	*Oral dose*: 200 ml	1.55 to 1.9 g/100 ml magnesium oxide with citric acid and sodium bicarbonate for effervescence. See precautions under magnesium sulfate.
Sodium phosphate	Usual oral dose is 4 g. The dose of the more palatable effervescent form is 10 g. This type also contains sodium bicarbonate and tartaric and citric acid. 1 g of the powder dissolves in 4 ml water.	Less active than sulfates (i.e., magnesium sulfate) as a laxative because it causes less mucosal irritation. When used for lead poisoning, lead is precipitated as a phosphate and is rapidly excreted in urine. Store in a tight container.
Fleet phosphosoda (sodium biphosphate, 16 g, sodium phosphate 6 g in an enema solution of 100 ml saline).	Given rectally as enema. Dose is 135 ml for adults and 75 ml for children.	Empties the colon in 2–5 min. Contraindicated if there is nausea or vomiting. Not recommended for children under age 6 months.
Fleet phosphosoda (48 g sodium biphosphate, monobasic, 18 g sodium phosphate dibasic, in 100 ml).	*Oral* dose: 10–20 ml in ½ glass cold water.	This preparation contains 14.96 g phosphorus per 100 ml or approximately 1.5 g phosphorus in 10 ml.

showed that nickel and iron ferrocyanides bound with an anion exchange resin, Amberlite, were effective in enhancing the excretion of ^{137}Cs in feces. The exchange compounds mentioned above are about as effective as Prussian Blue for ^{137}Cs contamination.

The oral use of strong cation or anion exchange resins, required for effective removal of most radionuclides, has declined because of increasing evidence of toxic side effects. However, if circumstances warrant the use of a strong ion exchange resin to decrease the absorption of a radionuclide from the intestine, then it should be given as soon as possible after the radionuclide ingestion for the most effectiveness. Most resins are relatively inert and pass through the gastrointestinal tract with little change, provided that they are chosen carefully and washed free of plasticizers and the residual monomers that are potentially toxic. Since the doses given are usually large, 3-15 grams, care must be taken to adjust the pH and the metal form of the resin to avoid too drastic a change in pH or bulk because of swelling while in the stomach or intestine. The resin has to be carefully chosen to have a high exchange capacity for the radionuclide in question at the pH's of both the stomach and intestine. Furthermore, the resin should be of small size, preferably less than 200 mesh, to achieve good mixing and present a large surface to the intestinal contents. The particles should be rounded rather than in the form of sharp shards in order to prevent abrasion or penetration of the intestinal wall. Finally, it must be kept in mind that the resins are likely to bind many charged species besides the elemental ions so that protracted use of some resins can interfere with absorption of necessary organic, as well as inorganic, nutrients.

No studies were noted in the literature of the usefulness of activated charcoal to decrease radionuclide absorption from the intestine, but it should be a potentially useful procedure. Until studies have delineated its usefulness, activated charcoal ingestion may be considered an untested alternative to ion exchange resins.

7.3.2.6 *Prussian Blue.* (See Table 7.4) Prussian Blue or Berlin Blue

TABLE 7.3—*Ion exchange drugs*

Compound	Route of Administration and Dose	Remarks
Sodium polystyrene sulfonate, USP. (Kayexelate, Winthrop-Stearns).	15 g (4 level teaspoons) to an adult. Give orally as a suspension in 4 ml of water or syrup/g of resin.	This resin is used medically for hyperkalemia and its usefulness for radionuclide uptake in the gut is not known but is assumed. May cause gastric irritation, anorexia, nausea, vomiting, and occasionally diarrhea. Could cause hypokalemia which in turn might exaggerate the effects of digitalis.
Activated charcoal, USP.	10 g given orally as a thick slurry in water. (About 2 tablespoons to an 8 oz water glass.)	Charcoal-radionuclide complex may or may not be sufficiently stable to survive transit through the intestine. If circumstances warrant also consider stomach lavage. (Section 7.3.2.2).

refers to ferric ferrocyanide, $Fe_4[Fe(CN)_6]_3$, in one of several forms. It is essentially not absorbed from the gastrointestinal tract, has low toxicity, and in finely divided colloidal soluble form it acts as an ion exchanger for some monovalent cations. Prussian Blue is well tolerated orally and if given promptly after ingestion of certain radionuclides decreases the initial absorption. When given orally after parenteral acquisition of the radionuclide, Prussian Blue picks up the radionuclide that is cycled through the intestine and prevents its reabsorption. For greatest benefit, treatment should begin promptly after radionuclide ingestion and be administered several times a day for a protracted period. Effectiveness of treatment is also related to the rate and amount of the radionuclide cycled into the intestine.

In animals, Prussian Blue has been found effective in accelerating the removal of cesium, thallium, and rubidium by the fecal route (Nigrovic, 1963; Richmond, 1968; Stather, 1972; Richmond *et al.*, 1975; Ducousso *et al.*, 1975). The compound has been used in man to remove cesium (Madshus *et al.*, 1966; Madshus and Strömme, 1968; Richmond, 1968). One gram of Prussian Blue given three times per day for several days, up to 3 weeks, is well tolerated in man (Strömme, 1968). It reduces the biological half-time of ^{137}Cs to a third of the usual value. Usually the K salt rather than the Na salt is used to avoid the possibility of removing K, although this has not been a problem.

Although obtainable from pharmaceutical firms in several European countries, Prussian Blue is not recognized by the U.S. Pharmacopeia and is not approved by the FDA. Radiogardase is a preparation of Prussian Blue marketed in Germany. If Prussian Blue is used in the U.S. the FDA should be approached for an emergency Investigational New Drug approval. The material is easily made up by a pharmacist or chemist. Preparation of Prussian Blue for research purposes has been described as follows: "The synthesis of Prussian Blue is straightforward. 40 ml of 0.5 M potassium ferrocyanide stock solution are diluted with 400 ml distilled water. To this mixture are added drop by drop 40 ml of 0.5 M ferric chloride solution with vigorous stirring. The blue precipitate is separated by centrifugation and re-dissolved in 250 ml distilled water. This is dialyzed for 24 hours against 2.5 l of distilled water with stirring to remove any free ferrocyanide ion. The dialysis is repeated, usually about 4 times, until the K^+ and Fe^{3+} content of the dialyzing media is negligible. The latter may be conveniently tested using atomic absorption analysis" (Richmond, 1968). Reagents should be prepared using the purest grade of chemicals available.

In situations where Prussian Blue is considered a possible useful agent for emergency treatment, the advance preparation of a supply and approval for its use for particular exposures should be done as part of medical emergency preparedness.

TABLE 7.4—*Prussian Blue*

Compound	Route of Administration and Dose	Remarks
Prussian Blue, Berlin Blue, [potassium ferric ferrocyanide; ferric hexacyanoferrate (II)].	1 gram given orally with water 3 times daily for up to 3 weeks or longer as required.	Not FDA approved for medicinal use. Human use beyond 3 weeks has not been reported to date. Constipation may be a side effect.
Nickel or ferric ferrocyanide-anion exchange resin.	1 gram given orally with water, then 0.5 gram every 6 hours for 7 days. Rest one week and then repeat if necessary.	Special resin form of Prussian Blue reported more beneficial than Prussian Blue alone. The nickel form was claimed better than the ferric complex especially when administered promptly after Cs ingestion. No side effects from the treatment were observed in two male humans given three separate weekly courses of treatment (Iinuma *et al.*, 1971).

TABLE 7.5—*Aluminum-containing antacid drugs*

Compound	Route of Administration and Dose	Remarks
Aluminum Phosphate Gel	*Oral* 100 ml single dose with water as soon after exposure as possible. Usual adult dose: 15–45 ml.	Preferred form for radiostrontium. Can cause constipation.
Aluminum Hydroxide Gel	*Oral* 100 ml in ½ glass of water as soon after exposure as possible.	Can cause constipation.

7.3.2.7 *Aluminum-containing Antacids.* (See Table 7.5) The aluminum-containing antacids are effective agents for reducing intestinal uptake of radioactive strontium. A single dose of 100 ml aluminum phosphate gel given immediately after exposure will decrease the intestinal absorption of radioactive strontium by about 85 percent (Spencer *et al.*, 1967; Spencer *et al.*, 1969a; Spencer *et al.*, 1969b). A single dose of aluminum hydroxide, 60–100 ml, given immediately after exposure will reduce the uptake by about 50 percent. Both drugs are non-toxic and well-tolerated.

7.3.2.8 *Alginates.* Alginates, salts of alginic acid, are jellylike substances obtained from the brown sea algae known as kelp. One widespread use of alginates is in the manufacture of ice cream. These substances inhibit the intestinal absorption of radioactive strontium. Ten grams of sodium alginate have been reported to decrease the absorption of acutely administered radiostrontium by a factor of 8 to 10 (Hesp and Ramsbottom, 1965) while smaller doses of 1.5 to 3 g will decrease absorption only by a factor of 2 (Harrison *et al.*, 1966). The dose of sodium alginate and the effect on the absorption of radiostron-

tium may be directly related (Hesp and Ramsbottom, 1965; Harrison *et al.*, 1966; Sutton, 1967; Carr *et al.*, 1968; Sutton *et al.*, 1971). A principal disadvantage in the use of most alginate compounds is their high viscosity that makes them difficult to ingest, although preparations of sodium alginate with relatively low viscosity (Sutton, 1967; Sutton *et al.*, 1971) are available, such as the low viscosity sodium alginate Manucol SSLD. In general, the alginates are too viscous to be of practical use. Incorporation of alginates into bread (Humphreys *et al.*, 1972) may be a more feasible way of administering this compound. In view of the difficulties of administration of this material and poor availability on demand in the United States, aluminum phosphate should be considered a preferable drug for inhibiting the uptake of radiostrontium after ingestion.

A commercial antacid (Gaviscon) contains 200 mg of alginic acid per tablet. Its use in this type of application is untested.

7.3.2.9 *Barium Sulfate.* (See Table 7.6) Barium sulfate is an insoluble salt used as a contrast medium for roentgenographic examination of the gastrointestinal tract. With the exception of constipation and occasionally fecal impaction, adverse effects have not been observed. Mineral oil is commonly used several hours after the barium sulfate as a prophylactic measure.

The principal indication for use of barium sulfate in treatment of ingested radionuclides is as an immediate antidote for strontium and radium absorption. Formation of the insoluble sulfates of these elements will markedly decrease their intestinal absorption.

7.3.2.10 *Phytates.* Significant amounts of phytates are found in grains and grain cereals, particularly in oats and soyabean products. Phytates contain phosphorus as phytic acid phosphorus, which combines with Ca, Mg, Zn, and Fe to form insoluble salts. Absorption of these elements from the intestinal tract can be reduced by the administration of phytates.

Sharpe *et al.* (1950) found a reduction of iron absorption to correlate with the solids content of test meals rather than the phytate content of rolled oats. Nevertheless, sodium phytates (0.2 g) reduced the absorption of iron by 15-fold, a finding indicating that added soluble

TABLE 7.6—*Barium sulfate*

Compound	Route of Administration and Dose	Remarks
Barium Sulfate (USP)	*Oral* 200–300 g in an aqueous suspension. *Rectal* 400–750 g	In prescribing barium sulfate, the name should be written legibly to avoid substitution of soluble barium sulfide or barium sulfite. These are toxic and can cause fatality.

phytates can interfere with iron absorption. Animal studies have shown that phytates also decrease the absorption of zinc, calcium, and magnesium.

Little is known about appropriate therapeutic doses of phytates. Sodium phytate has been given orally, 9 g daily, for 11 days in human research studies. It is no longer marketed and is apparently not available. Administration of phytates would thus be available only by natural food selection.

7.3.3 *Blocking and Diluting Agents*

7.3.3.1 *Introduction.* A blocking agent saturates the metabolic processes in a specific tissue with the stable element and thereby reduces the uptake of the radionuclide. The best example of this process is the use of stable potassium iodide to prevent the uptake of radioiodine in the thyroid. To be effective, blocking agents must be administered in a form that is rapidly absorbed.

Isotopic dilution with a diluting agent is achieved by the administration of large quantities of the stable element or compound so that, on a statistical basis alone, the opportunity for incorporation and exposure to the radionuclide is lessened. The best example here is the use of water to reduce the effective half-life of tritium in the body. As with blocking agents it is desirable to administer a form of the diluting agent that is at least as readily absorbed and metabolized as the compound that contains the radioisotope.

Displacement therapy is a special form of dilution therapy in which a non-radioactive element of a different atomic number successfully competes with the radionuclide for uptake sites. An example is the use of calcium to reduce the deposition of radiostrontium.

7.3.3.2 *Iodides.* To be effective as blocking agents, stable iodide compounds must be given as soon as possible after the exposure to radioiodine. A dose of 300 mg of iodide, as administered by a dose of 390 mg potassium iodide, provides maximal blocking. Any readily available soluble form of iodine with equivalent iodide content is suitable. Some cough syrups contain sufficient iodide to achieve an effective dose. Enteric coated tablets should be crushed or a more rapidly absorbed form should be used if possible. Stable iodides should be administered for about 7 to 14 days to prevent recycling of the radioiodine into the thyroid.

See Section 7.3.4.2, *Antithyroid Drugs*, for more discussion and drug listings. Refer also to NCRP Report No. 55 (1977b) entitled, *Protection of the Thyroid Gland in the Event of Releases of Radioiodine.*

7.3.3.3 *Strontium Compounds.* (See Table 7.7). Stable strontium is

useful as a diluting agent for radiostrontium. It is available in either tablet or intravenous solution forms.

(a) Strontium Lactate can be given orally in doses of 500–1500 mg strontium as the lactate per day. It is well tolerated and is non-toxic at this dosage. It can be given daily for several weeks.

(b) Strontium Gluconate can be given intravenously at a dose of 600 mg daily for up to 6 consecutive days. It will increase the urinary ^{85}Sr excretion by a factor of 2 to 3.

7.3.3.4 *Phosphate.* (See Table 7.8). Phosphate can be used to decrease the intestinal absorption of radioactive strontium (Spencer *et al.*, 1964; 1973b). Oral phosphates can be given in inorganic or organic forms. Vomiting, diarrhea, or both, may occur from phosphate administration in doses that exceed 2 g per day.

Oral administration of neutral phosphates (monobasic or dibasic sodium phosphate and monobasic or dibasic potassium phosphate) is used in the treatment of mild or moderate hypercalcemia. The mechanism of the hypocalcemic action of phosphates is not clearly understood, but it is known that phosphate therapy does not enhance excretion of calcium from the body and may result in deposition of calcium in tissues.

Intravenous phosphate infusion is generally reserved for severe hypercalcemia emergencies and is an unlikely drug candidate for use in radionuclide uptakes. Medical misadministration of soluble ^{32}P may be an indication for its use. This mode of phosphate administration must be carried out cautiously because if administered too rapidly it can cause severe hypotension, renal failure, and myocardial infarction. The serum calcium level and electrocardiogram should be monitored during infusion.

Both sodium and potassium phosphate are saline cathartics. The usual adult oral dose is 4 g. Sodium salts are contraindicated in cardiac patients with edema or with evidence of congestive heart failure or for those on a low-sodium diet. Potassium salts must be given cautiously to patients with cardiac disease because the absorbed potassium ion will depress cardiac function when renal function is impaired.

TABLE 7.7—*Strontium compounds*

Compound	Route of Administration and Dose	Remarks
Strontium Lactate (Strontolac, Wyeth Pharmaceutical Co.)	*Oral* 300 mg strontium given from 2–5 times daily.	Well tolerated. Should be given with meals.
Strontium Gluconate (investigational (IND) drug, Sandoz Pharmaceutical Co.)	*Intravenous* 600 mg strontium per day.	Infuse in 500 ml 5 percent glucose in water for 4 hours. Can be given on 6 consecutive days.

TABLE 7.8—*Phosphate drugs*

Compound	Route of Administration and Dose	Remarks
Sodium Glycerophosphate	*Oral* Adult dose, 600–1200 mg phosphate to be given in divided doses.	Not USP but in British Pharmacopeia. Well tolerated. The larger dose may result in increased number of soft bowel movements. Chemical grade of sodium glycerophosphate has been used without problem.
Sodium Phosphate (Na_2HPO_4) or, Potassium Phosphate (K_2HPO_4; Hyperphos-K)	*Oral* Adult dose, 600–1200 mg to be given in divided doses.	Larger dose (4 g) used as saline cathartic (see Section 7.3.2.4).
Neutral Potassium or Sodium Phosphate (Neutra-Phos K, K-Phos Neutral, Neutra-Phos)	*Oral* Adults, 24 ml of 1 molar dibasic sodium or dibasic potassium phosphate or a mixed neutral salt of monobasic and dibasic sodium phosphate four times daily to supply 3 g of phosphorus in the treatment of hypercalcemia.	U.S. recommended daily allowance of phosphorus is 1 g for adults and children over 4 years of age. Sodium salt must be avoided if renal function is inadequate. Potassium phosphate may be used in that case, but not in cardiacs.

TABLE 7.9—*Forced fluids*

Compound	Route of Administration and Dose	Remarks
Water (including fruit juices, tea, coffee, beer)	*Oral* 3000–4000 ml/day.	Usually forced to the tolerance level by patient. Check urine volumes and save voidings separately for radioassay.
5 percent glucose in water or saline	*Intravenous* Up to 3000 ml/day.	Used only if fluids cannot be given orally. Usual precautions on electrolyte balance (sodium and potassium) must be observed.

7.3.3.5 *Forced Fluids.* (See Table 7.9). In cases of exposure to tritium, it is possible to increase its excretion by forcing fluids orally. It would be unusual to resort to intravenous fluids although these might be considered if oral fluids cannot be maintained at an adequate level. The usual precautions must be observed in persons with cardiovascular or renal impairment.

7.3.3.6 *Calcium.* (See Table 7.10). Orally or intravenously administered calcium is effective in increasing the urinary excretion of radioactive strontium and calcium in man. Oral calcium is also useful in reducing intestinal absorption of radioactive calcium.

7.3.3.7 *Zinc.* (See Table 7.11). Oral zinc can be used for isotopic dilution in cases of exposure to zinc-65 if CaDTPA is not immediately available.

TABLE 7.10—*Calcium compounds*

Compound	Route of Administration and Dose	Remarks
Calcium Gluconate tablets	*Oral* 15 g daily in divided doses is usual adult dose for hypocalcemia.	May cause constipation.
Calcium Lactate tablets	*Oral* 4 g three times daily is usual adult dose for hypocalcemia.	May cause constipation.
Calcium Gluconate ampoules	*Intravenous* 5 ampoules each containing approximately 500 mg calcium can be given in 500 ml 5 percent glucose in water over 4 hours.	Can be given daily on 6 consecutive days. Intravenous calcium should not be given to persons receiving quinidine or digitalis preparations or to those who have a very slow heart rate.

TABLE 7.11—*Zinc compounds*

Compound	Route of Administration and Dose	Remarks
Zinc Sulfate	*Oral* 660 mg zinc sulfate (about 150 mg zinc) per day can be given in 3 or 4 divided doses.	Take with a meal to prevent gastric irritation.

7.3.3.8 *Potassium.* (See Table 7.12). Oral potassium compounds should be considered for isotopic dilution in cases of internal exposures to radioactive potassium. The principal radioactive potassium isotope (^{42}K) has a short half-life (12 hours) so emergency situations that require treatment will need a very fast response time. Therapeutic efforts may not be adequate to influence radiation doses appreciably.

Liquid preparations are the favored form for oral therapy. All commercial liquid preparations must be well diluted before ingestion, usually with fruit juice or water. Administration after food is advisable in order to minimize gastric irritation. Intravenous administration of potassium is not advisable unless the patient is not able to take potassium orally.

Potassium is contraindicated in patients with hyperkalemia from any cause: acute dehydration, heat cramps, severe renal impairments, and untreated Addison's Disease. It should be used with caution in the presence of cardiac disease.

7.3.4 *Mobilizing Agents*

7.3.4.1 *Introduction.* Mobilizing agents are compounds that increase a natural turnover process and thereby induce a release of some forms

TABLE 7.12—*Potassium compounds*

Compound	Route of Administration and Dose	Remarks
Potassium chloride (Kay Ciel Elixir, Cooper; K-Lor, Abbott; K-Lyte, Meade Johnson; Kaochlor Liquid, Warren-Teed)	*Oral* 10–15 mEq in liquid preparation 3–4 times/day. *Intravenous* 100–300 mEq/day (10–15 mEq/hour)	*Oral route*: Potassium tablets are not advised because uncoated tablets may cause small bowel ulceration and the rate of potassium absorption is unreliable. A liquid potassium preparation which must be diluted with fruit juice or water is preferred. Patients receiving potassium should have normal kidney function. *Intravenous route*: Intravenous infusions should be given at a concentration not greater than 40–60 mEq/liter. May cause pain if injected in small vein. Contraindicated in patients with renal impairment, untreated Addison's Disease, and in hyperkalemia of any cause. Use with caution in presence of cardiac failure. Check serum potassium level and urinary potassium excretion.
Potassium gluconate (Kaon, Warren-Teed)	*Oral* 15 ml liquid preparation given in 30 ml water or fruit juice (2–4 times per day)	Give after meals to reduce gastric irritation. Patient should have normal kidney function for its use.
Potassium bicarbonate	*Oral* Usual dose is 1 g 4 times per day (range 0.5–2.0 g)	Very well tolerated. Not readily available as capsules.

of radioisotopes from body tissues. This process results in an enhanced rate of elimination from the body. Mobilizing Agents are more effective the sooner they are given after the exposure to the isotope. Many of the mobilizing agents are still effective, however, within about 2 weeks after exposure to the radioisotopes, although they are decreasingly effective after this time interval.

Chelating agents may be considered to be a special class of mobilizing agents and are discussed in Section 7.3.5.

7.3.4.2 *Antithyroid Drugs.* (See Table 7.13). In order to reduce the uptake of radioiodine by the thyroid, several antithyroid drugs may be considered. The normal thyroid takes up approximately 80-100 micrograms of iodide per day (Freeman and Blaufox, 1973; Gilman and Murad, 1975). The speed with which the gland takes up iodide depends on the thyroid stores and utilization of iodine. After uptake, iodine is oxidized and incorporated into tyrosine as monoiodo- or diiodotyrosine. Coupling then occurs to form thyroxine (T_4) and triiodothyronine (T_3). These hormones are stored as thyroglobulin. Once iodine is in the gland its turnover is slow. The biological half-time is about 120 days (Bernard *et al.*, 1963).

The most effective method of preventing uptake of radioiodine is to administer potassium iodide, which is primarily a blocking agent (Section 7.3.3.2). MgI_2 or NaI is also effective. One blocking dose of 300 mg of iodide, if given within 30 minutes, will stop further uptake of radioiodine by the thyroid. Only about 50 percent of the uptake is blocked if the iodide administration is delayed six hours and little effect can be achieved if the delay is more than 12 hours (Ramsden *et al.*, 1967). If stable iodide is given after the first 24 hours, it may sometimes prolong the retention of iodine since it suppresses the release of thyroid hormone. Von Henreich *et al.* (1966) showed that after an initial blocking dose, additional daily supplemental doses of iodide should be given over the next 8 days to prevent the small amount of radioiodine that leaves the gland from being recycled.

Toxic reactions from a brief course of iodide treatment should be rare. A few individuals, however, are sensitive and may develop angioedema. Chronic iodide poisoning, or iodism, can also occur but only after ingesting iodides for several weeks or longer. Symptoms and signs include sialadenitis, rhinitis, conjunctivitis, headache, drug fever, and skin rashes. In either acute or chronic toxicity reactions, withdrawal of the medication and supportive care is all that is necessary and symptoms disappear within a few days.

Propylthiouracil (PTU) and methimazole (MMI) directly interfere with the oxidation of the iodide ion and block the formation of hormone. These drugs are absorbed from the GI tract within 20 to 30 minutes. The effect, however, declines rapidly and blockage of the thyroid hormone formation lasts only about 6 to 8 hours. Thirty milligrams of MMI has approximately the same inhibitory effect as stable iodide if given promptly after exposure (Tanaka *et al.*, 1968). If the thyroid already has a plentiful supply of stable iodine, or if stable iodide has already been administered, the response of the gland to these drugs is greatly reduced (Gilman and Murad, 1975). Both drugs are metabolized rapidly and have to be administered every 8 hours for maximum effectiveness. PTU decreases the urinary excretion of radioiodine by 30 to 40 percent, increases hepatic accumulation, and decreases the rate of disappearance of protein bound iodine from the serum (Morreale de Escobar and Escobar del Rey, 1967).

Unpleasant side effects occur in about 3 percent of patients who take PTU and in about 7 percent who take MMI (Gilman and Murad, 1975). The most common reaction is a papular and pruritic rash. Pain and stiffness in the joints, paresthesias, headache, nausea, and loss or depigmentation of hair are less frequent toxic reactions. The most serious side effect is agranulocytosis, which occurs in about 1 in 500 cases (Gilman and Murad, 1975).

Potassium thiocyanate (KSCN) blocks the uptake of iodide by the thyroid by abolishing the thyroid-to-plasma iodide gradient. Normally the concentration of iodine in the gland exceeds that in the serum by as much as 50 to 1 in a euthyroid patient and 100 to 1 in a hyperthyroid patient. A single dose of thiocyanate will reduce the iodide-concentrating capacity of the thyroid gland and will increase the discharge of stored iodide.

Potassium or sodium thiocyanate is moderately toxic. There is a direct correlation between incidence and severity of reactions and serum concentration. If serum levels do not exceed 8 to 12 mg/100 ml, toxic effects are usually mild, Many patients experience lassitude, fatigue, malaise, and drowsiness. Nausea, vomiting, diarrhea, dizziness, and headache also occur frequently. Exfoliative dermatitis rarely occurs, but can be fatal. Central nervous system reactions include irritability, blurred vision, tinnitus, motor aphasia, hallucinations, and delirium (Goodman and Gilman, 1975). Although once commonly used as an antihypertensive medication, thiocyanates are not now available in most pharmacies. They should probably not be considered for treatment of radioiodine exposure because of the potential toxicity and limited therapeutic effectiveness.

Sodium or potassium perchlorate reduces radioiodine uptake, hastens its excretion, and diminishes recycling in experimental animals (Van Middlesworth, 1975). This material, however, is an experimental drug and is not approved for general medical use at this time.

Thyroid hormone causes suppression of thyrotropin from the pituitary gland and so reduces T_3 and T_4 release, but this mechanism is too slow to be of value in the immediate post-exposure situation. When thyrotropin is administered, it causes a prompt reduction in the amount of stored radioiodine in the gland. All phases of hormone synthesis are also stimulated but not rapidly as is the release. Although the more rapid release of hormone containing radioiodine might at first appear desirable, the increased uptake of recycled radioiodine may be self-defeating.

Several antithyroid drugs have been compared in man for their effectiveness in accelerating the discharge of ^{131}I already fixed in the thyroid (Tanaka *et al.*, 1968). When 40 mg of MMI was given daily to three volunteers several days after the administration of 15 to 35 μCi of ^{131}I, its effective half-life was reduced an average of about 25 percent and the biological half-time an average of about 50 percent. One gram per day of KSCN reduced the effective and the biological half-lives less than 5 percent in one patient. $KClO_4$ was ineffective in two patients and 100 mg NaI per day reduced the effective half-life 12.2 percent and the biological half-time 23.4 percent.

Because of the reasons outlined above, stable iodides are clearly the drugs of choice to prevent uptake of radioiodine. Ideally they should be administered at the site of the accident and as soon as possible after an exposure has occurred. Six drops of saturated solution of potassium iodide in a glass of water or 300 mg of KI in tablet form should be given. Enteric coated tablets should be crushed. Even if subsequent studies show the exposure to be insignificant, the incidence of toxic reactions to iodides is so low that no harm will be done. If more than 12 hours have passed since the initial exposure to radioiodine and the estimated dose is sufficiently high to be concerned about possible radiation effects, other antithyroid drugs, such as propylthiouracil or methimazole, may be useful to reduce the thyroid's retention of the radioiodine.

See also NCRP Report No. 55 (1977b) entitled, *Protection of the Thyroid Gland in the Event of Releases of Radioiodine.*

7.3.4.3 *Ammonium Chloride.* (See Table 7.14). This chemical is an acidifying salt, which when given orally is an effective mobilizing agent for radiostrontium deposited in the body. Its effectiveness can be enhanced by the simultaneous use of intravenous calcium (500 mg calcium as the gluconate) given in 500 ml 5 percent glucose in water over 4 hours on 3 to 6 consecutive days. This combined treatment is most effective if started as soon as a significant deposition of radiostrontium is identified, although some effectiveness is still demonstrable if begun as long as two weeks after exposure (Spencer *et al.*, 1965). An estimated reduction in the body burden of radiostrontium of

TABLE 7.13—*Antithyroid drugs*

Compound	Route of Administration and Dose	Remarks
Saturated Solution of Potassium Iodide	*Oral* 6 drops (approximately 300 mg KI) in a glass of water immediately, then 6 drops daily for 7–14 days.	Most readily available. Low toxicity. Also available as potassium iodide liquid 500 mg/tablespoon, which is used as a potassium supplement for patients on diuretics.
Potassium Iodide USP	*Oral* In solid form, 300 mg immediately, then 300 mg daily for 7–14 days.	Enteric-coated tablets should be crushed for faster absorption.
Strong Iodine (Lugol's) Solution	*Oral* 2 ml in water, then 1 ml daily for 8 days.	Rapidly absorbed. Each ml contains: Iodine–50 mg, KI–100 mg.
Propylthiouracil	*Oral* 50 mg tablets. 100 mg every 8 hours for 8 days.	See text regarding toxicity.
Methimazole	*Oral* 10 mg every 8 hours for 2 days. Reduce to 5 mg and continue for another 6 days.	See text regarding toxicity.

between 40 and 75 percent may be obtained under ideal circumstances. This regimen will also increase urinary calcium and phosphorus excretion.

In full therapeutic doses, ammonium chloride frequently causes gastric irritation, nausea, and vomiting. Occasionally, the drug produces hepatic coma in patients with severe liver disease because of the inability of the damaged liver to metabolize ammonia.

Ammonium chloride is marketed by many manufacturers under its generic name in 500 mg tablets (enteric-coated).

7.3.4.4 *Diuretics.* (See Table 7.15). These drugs decrease the volume of extracellular fluid by enhancing urinary excretion of sodium and water, usually by inhibiting the reabsorption of sodium by the renal tubules. Their usefulness in the treatment of internal radionuclide deposition is untested. Enhanced excretion of sodium, chloride, potassium, bicarbonate, magnesium, and water occurs with an induced diuresis. Some corresponding radioisotopes that could be involved in radiation accidents are ^{22}Na, ^{24}Na, ^{38}Cl, ^{42}K, and ^{3}H.

The diuretics are classified as xanthines, osmotic agents, mercurial compounds, carbonic anhydrase inhibitors, thiazides and related sulfonamide compounds, and miscellaneous other agents. The thiazides and related sulfonamide compounds, ethacrynic acid, and furosemide are potent diuretics that might be selected for therapeutic trial after high exposures to the radionuclides.

Side effects noted with the use of these drugs include dehydration, electrolyte disturbances (hypokalemia, hyponatremia), headache, nausea, gastrointestinal disorders, dizziness, syncope, and dermatitis. The thiazides may increase the serum levels of uric acid, calcium, and fasting blood sugar. Hyperuricemia may occur also with the use of ethacrynic acid and furosemide. The adverse reactions of each individual agent should be reviewed and considered before it is used.

The proper use of ethacrynic acid and furosemide requires an understanding and anticipation of the electrolyte and fluid derangements that they may induce. Intravenous forms are available also for these potent and short-acting drugs. Furosemide is recommended for calcium excretion.

7.3.4.5 *Expectorants and Inhalants.* (See Table 7.16). Expectorants are compounds used to stimulate the flow of respiratory tract secre-

TABLE 7.14—*Ammonium chloride*

Compound	Route of Administration and Dose	Remarks
Ammonium Chloride	*Oral* 1-2 gm four times/day.	Can be given up to 6 consecutive days. Check total serum CO_2 or pH of blood which decrease during ammonium chloride administration.

TABLE 7.15—*Diuretic drugs*

Thiazides	Daily Dosage Range (mg)	Duration of Action (Hours)
Chlorothiazide (Diuril)	500 to 1,000	6 to 12
Hydrochlorothiazide (Esidrix, HydroDiuril, Oretic)	25 to 200	12 to 18
Benzthiazide (Aquatag, Exna)	25 to 200	12 to 18
Hydroflumethiazide (Saluron)	25 to 50	18 to 24
Bendroflumethiazide (Naturetin)	5 to 20	More than 18
Methyclothiazide (Enduron)	2.5 to 10	More than 24
Trichlormethiazide (Metahydrin, Naqua)	2 to 4	More than 24
Polythiazide (Renese)	1 to 4	24 to 48
Cyclothiazide (Anhydron)	1 to 2	18 to 24
Related Sulfonamide Compounds		
Chlorthalidone (Hygroton)	50 to 200, usually on alternate days	24 to 72
Quinethazone (Hydromox)	50 to 200	18 to 24
Miscellaneous Diuretics		
Ethacrynic Acid (Edecrin)	50 to 400	6 to 12 hours. Peak action at 2 hours.
Furosemide (Lasix)	40 to 80	6 hours. Acts within 1 hour.

tions by decreasing the sputum viscosity and increasing the volume. These are commonly used for the treatment of respiratory disorders in which bronchial secretions are excessive, thick, or purulent. Expectorants may be given orally or administered by aerosol inhalation.

The fluid compounds used for inhalant administration may be classified as: (1) hypertonic saline solutions to increase respiratory fluid volume by osmosis; (2) hygroscopic agents, such as propylene glycol or glycerine, which reduce the viscosity of bronchial secretions by attracting more water; (3) detergent mixtures, such as Alevaire, to increase wetting and thereby liquify mucous; and (4) mucolytic agents, some of which, such as acetylcysteine (Mucomyst), act through their ability to depolymerize mucopolysaccharides while others, such as pancreatic dornase (Dornavac), hydrolyze deoxyribonucleoprotein.

Studies on the effects of these agents on inhaled radioactive particles have been disappointing (Bair and Smith, 1969). None provides effective action that would be dependable or particularly useful in the treatment of persons who have accidentally inhaled radioactive particles. While they sometimes may aid the mechanical transport of particles on the mucociliary blanket of the tracheobronchial tree, it appears that expectorants or inhalants cannot be expected to help in the removal of particles from the alveolar area of the lung. These retained particles are of greatest importance in the long-term radiation dose to the lung as well as for possible redistribution to other organs. Tombropoulos (1964) concluded that there was greater probability of increased particle clearance from the lung in rats with the use of agents that decreased mucous secretion, whereas increased secretion tended

to increase retention. One exception to this general observation was NH_4Cl, which was thought to increase secretions and appeared to be mildly helpful. Mucolytic agents including pancreatic dornase, and surface active agents, including Alevaire, Pluronics F-68, Triton and Tween-80, were ineffective in removing radioactive particles from the lungs of rats (Tombropoulos *et al.*, 1964; Willard *et al.*, 1958; Willard, 1959).

In view of the discouraging results in initial animal studies aimed at treating inhaled radioactive particles, the use of expectorant drugs and inhalants cannot be recommended as a therapeutic procedure after inhalation of radioactive particles. There is need, however, for further scientific study to confirm these initial animal studies.

7.3.4.6 *Parathyroid Extract (PTE).* (See Table 7.17). Parathyroid extract injections can increase the serum calcium level by mobilizing calcium from bone and relieve symptoms of hypoparathyroid tetany. PTE promotes the urinary excretion of calcium and phosphorus. The removal of radioactive strontium from the body by PTE is associated with the increased urinary excretion of calcium that follows the decalcification induced by PTE.

Parathyroid hormone has been used to treat an accidental overdose of radiophorphorus (^{32}P) in man. The combination of 200 units of parathyroid extract intramuscularly every 6 hours, IV calcium gluconate (540 mg Ca daily), and 5 g of oral phosphorus as the buffered sodium salt daily reduced the radiation dose to bone marrow by an estimated 38 percent (Cobau *et al.*, 1967). The effective half-life of the ^{32}P decreased from 11.2 to 4.8 days, equivalent to a sevenfold increase in the rate of isotope excretion. Treatment did not start until the ninth day after ^{32}P administration. Earlier initiation of the program of phosphate diuresis probably would have resulted in a greater reduction in marrow irradiation dose.

7.3.4.7 *Corticosteroids.* (See Table 7.18). Adrenal corticoids are used

TABLE 7.16—*Expectorants and Inhalants*

Compound	Route of Administration and Dose	Remarks
Ammonium Chloride	*Oral* 5 ml of syrup (equal to 300 mg of NH_4Cl).	Can produce metabolic acidosis. Use cautiously in patients with impaired function of the liver, kidney or lungs.
Glyceryl Guaiacolate	*Oral* 100–200 mg 2–4 times per day as syrup.	Nausea, gastrointestinal upset, and drowsiness occur infrequently.
Sodium Chloride	*Inhalation* Isotonic or 0.5 M NaCl nebulized to form a mist.	Prolonged inhalations can cause irritation of bronchial mucosa.

TABLE 7.17—*Parathyroid extract*

Compound	Route of Administration and Dose	Remarks
Parathyroid hormone extract	40 units, intramuscular every 12 hours to increase the serum calcium. 50–150 units/12 hours for acute tetany. When used intravenously, PTE should be added to other intravenous solutions, e.g., 5 percent dextrose in water.	Overdosage can lead to hypercalcemia which is associated with signs such as vomiting, constipation, muscle atony, and uremic coma. Sodium chloride solutions often cause a precipitate to form.

mainly for two purposes: (1) in physiologic doses to correct adrenal deficiency; and (2) in pharmacologic doses to treat inflammatory conditions, allergic states, collagen disorders, and certain other diseases. The long-term use of pharmacologic doses of systemic corticosteroids can induce hypercorticism and other adverse reactions, such as an increase of the urinary calcium and the development of osteoporosis. The increase of the urinary calcium has been shown to be associated with about a 3-fold increase in the level of urinary radiostrontium excretion when the corticosteroid is given at the time of exposure to radiostrontium (Spencer *et al.*, 1963). It is also expected that corticosteroids would result in some release of previously deposited radioactive strontium, although this has not been demonstrated experimentally. In view of their possible adverse effects and limited therapeutic effectiveness, corticosteroids are not recommended as a drug of choice in treating radiostrontium exposures. They do offer one additional treatment option in the event of serious cases where minor therapeutic gains may outweigh the risks.

7.3.5 *Chelating Agents*

7.3.5.1 *Introduction.* A number of chemical compounds are known that enhance the elimination of metals from the body by chelation, a process by which organic compounds (ligands) exchange less firmly bonded ions for other inorganic ions to form a relatively more stable nonionized ring complex. The strength of this binding varies with the different chelating agents and with the bonded ion. These agents do not have the ability to form a chelate with only one specific cation, but they do bond some metals more strongly than others. After chelation, the cation becomes an integral part of a stable ring structure and ceases to act as a free ion. When this complex is soluble it can be excreted readily by the kidney.

A properly selected and administered chelating drug will enhance the excretion of some radioactive elements, including the transuranium metals, and thus reduce their residence time in the body (Volf, 1978; Catsch and Harmuth-Hoene, 1979). Therapy with a chelating agent is most effective when it is begun immediately after exposure while the metallic ions are still in circulation and before their incorporation within cells or deposition in tissues such as bone. Chelating agents can still increase excretion later, with continued or intermittent use, although with lesser effectiveness, because of metabolic recycling of the radionuclide into the extracellular fluid compartments. In some instances, intracellular chelation appears to take place.

The effectiveness of chelation *in vivo* is influenced by many factors. Endogenous substances, such as hemosiderin, hemoglobin, ferritin, various enzymes, and nucleic acids can interfere with the action of chelating agents. Deviations from the normal pH of blood and urine will alter the degree of ionization of both the chelating drug and the metal ions to be complexed.

Evaluation of the therapeutic effectiveness of chelating agents in a particular exposure situation is based on measurement of the radionuclide excretion rates in urine before and after treatment. Whole body counting for some radionuclides may provide data for estimating the effective half-life and thus measure therapeutic effectiveness by

TABLE 7.18—*Corticosteroid drugs*

Compound	Route of Administration and Dose	Remarks
Prednisone	*Oral* 5–20 mg daily.	Adverse reactions include retention of sodium and water; potassium loss. Long-term use can lead to protein catabolism, muscle weakness, osteoporosis, peptic ulcer, pancreatitis, ulcerative esophagitis, neurological problems such as convulsions, endocrine problems such as Cushingoid state, decreased carbohydrate tolerance, and opthalmologic problems such as glaucoma.
Cortisone Acetate	*Oral* 15–30 mg/day for anti-inflammatory and other chronic disease conditions. 75–150 mg/day for serious chronic disease.	
Dexamethason (Decadron)	*Oral* 0.5–10 mg/day. *Intravenous or intramuscular* 4–20 mg of Dexamethason sodium phosphate.	
Methylprednisolone (Medrol)	*Oral* 4–16 mg/day. *Intramuscular* (acetate) 40–20 mg/day. *Intravenous* (Na succinate) 100–250 mg every 4–6 hours for shock or 10–40 mg for other conditions.	

comparison with the anticipated half-life. Such evaluations are necessary for judging when treatment is no longer effective enough to warrant continued administration of the drug.

7.3.5.2 *EDTA.* (See Table 7.19). The calcium salt of ethylenediaminetetraacetic acid (calcium edetate, $CaNa_2EDTA$) is the most common form used in man, primarily to treat lead poisoning. It also can be used to chelate zinc, copper, cadmium, chromium, manganese, and nickel, but is not effective for mercury, arsenic, or gold. It has effectiveness for the transuranium metals, such as plutonium and americium, but $CaNa_3DTPA$ (see Section 7.3.5.3) is about an order of magnitude more effective. Nevertheless, $CaNa_2EDTA$ may be selected as a substitute therapeutic agent for $CaNa_3DTPA$, if the latter is not available for immediate use.

The sodium salt of EDTA (Na_3EDTA) is used only for enhancing calcium excretion in hypercalcemia. It is not recommended for treatment of heavy metal poisoning because of the much greater potential toxicity of the drug. It can cause hypocalcemic tetany when administered rapidly or in large doses by the intravenous route.

The most common adverse reactions to the edetates are gastrointestinal upset and pain at the site of injection. Transient bone marrow depression, mucocutaneous lesions, chills, fever, muscle cramps, and histamine-like reactions (sneezing, nasal congestion, and lacrimation) have also been described. The edetates are nephrotoxic and, although rare, fatalities have been associated with large doses (American Medical Association, 1977). For this reason, EDTA must be used with extreme caution in patients with pre-existing renal disease.

7.3.5.3 *DTPA.* (See Table 7.20). The powerful chelating agent, diethylenetriaminepentaacetic acid (DTPA), is generally more effective in removing many of the heavy metal, multivalent radionuclides than its better known homologue, EDTA. Like the latter, the chelates formed with many heavy metals are water soluble and excreted via the kidneys, but the DTPA metal complexes are more stable and less likely to release the radionuclide before excretion. After intravenous administration, the agent is excreted rapidly with about 50 percent appearing in urine in the first hour. Treating promptly with the highest recommended dose of the chelate produces the greatest enhancement of the radionuclide excretion. The effectiveness of treatment at later times following a radionuclide uptake is directly related to the solubility of the metal *in vivo* and its presence in the extracellular spaces (Volf, 1979; Catsch and Harmuth-Hoene, 1979).

The calcium and zinc salts of DTPA are both approved for human use. They are available under Investigational New Drug (IND) permits for treatment of persons contaminated internally with plutonium.

TABLE 7.19—*Chelating drug EDTA*

Compound	Route of Administration and Dose	Remarks
CaEDTA (calcium disodium edetate, calcium disodium Versenate, calcium disodium edathamil)	*Intravenous* Maximal dose is 75 mg/kg of body weight daily, given in two divided doses, up to a maximal dose of 375 mg/kg weekly. Maximal dose for total regimen normally should not exceed 550 mg/kg. Administer in 250–500 ml of 5 percent glucose in water or isotonic saline. (Note: Above dose schedule is for treating lead poisoning. Dose for radioactive metal poisoning may be reduced to about ½ of maximums listed.)	Infusion time should be about 1 hour for each 1 g EDTA. It is not advisable to exceed two courses of EDTA with a 1-week rest interval in adults. CAUTION: Kidney function must be normal. Check urine for albumin before and after EDTA infusion. Discontinue treatment if albuminuria occurs.
	Intramuscular 75 mg/kg as 20 percent solution in 0.5 to 1.5 percent procaine; this amount given in three equally divided doses every eight hours. Drug is prepared in procaine solution since intramuscular injection is extremely painful. Pain persists after the effect of the procaine wears off.	IM administration is used primarily as a diagnostic test for lead poisoning; it is not indicated for chelation therapy.
	Oral Not recommended.	Oral EDTA causes abdominal discomfort and diarrhea.
NaEDTA (Disodium edetate, Endrate, Sodium salt of ethylenediaminetetraacetic acid)	50 mg/kg body weight infused intravenously in 500 ml 5 percent glucose in water or isotonic saline over 3–4 hours. Do not exceed 3 gm in 24 hours. Daily infusions can be given for 5 days, this course can be repeated after a 6-day rest period, if necessary.	Ca gluconate should be available during NaEDTA infusions in case acute hypocalcemia develops. Toxicity is related to total dosage and speed of infusion. Avoid extravasation into tissue when infusing NaEDTA. Check blood pressure and urine for albumin during and after infusion. EDTA should not be given to patients with renal disease. Liver function tests should be normal before beginning infusions. *Do not* give undiluted injections of NaEDTA.

Experimentally, in animals, DTPA has been used as the sodium, calcium, and zinc salts. The sodium salt (NaDTPA) chelates calcium in the body and can induce tetany. It is not recommended for therapeutic use.

CaDTPA and ZnDTPA effectively chelate the transuranium metals (plutonium, americium, curium, californium, and neptunium), the rare earths (such as cerium, yttrium, lanthanum, promethium, and scandium), and some transition metals (such as zirconium and niobium). Their clinical use has been primarily for treatment of plutonium and americium exposures.

The efficacy of CaDTPA and/or ZnDTPA treatment for plutonium incorporations is highly dependent on the solubility and chemical form of the plutonium. Their effectiveness is good for soluble salts, such as the nitrate or chloride, but is essentially nil for highly insoluble compounds, such as the high-fired oxide. The same characteristics are noted experimentally when a monomeric form (soluble) of plutonium is administered that gradually converts to polymeric forms (less soluble) as it is distributed and deposited in various tissues in the body. Thus, chelation is highly dependent not only on the element itself, but also on the chemical and physical characteristics of the compound at the time of DTPA administration.

Clinical experience with CaDTPA includes use by intravenous injection and administration as an inhalant aerosol. The most effective dose schedules have not been determined with certainty. This question is further complicated by recognition of the lesser toxicity of ZnDTPA and possible advantages of administering combinations of chelating agents.

The substance of these unresolved issues may be summarized as follows: (1) CaDTPA is more effective than ZnDTPA in rats when given promptly after exposure to ^{239}Pu, ^{252}Cf, and ^{241}Am (Volf, 1976; Seidel, 1976). No comparable studies are available in man. This difference between DTPA salts is apparently significant for only the first day or two after exposure according to results in the animal studies. (2) ZnDTPA is less toxic than CaDTPA and should be advantageous for longer term treatments and especially for continuous or fractionated treatments (Taylor *et al.*, 1974). (3) Studies in rats indicate that combined administration of DTPA and another chelating agent, DFOA (desferrioxamine, see Section 7.3.5.6), may be more effective than DTPA alone (Smith, 1964b; Volf, 1974; 1975; 1976; 1979; Volf *et al.*, 1977). This combination is untried in humans and the potential toxicity from such combinations has not been investigated sufficiently.

The dose schedules given in Table 7.20 describe a reasonable standard regimen, but it must be noted that the experience in human therapy is inadequate to justify the assertion that any one schedule of treatment is preferable in a specific exposure situation. Each additional experience in man should be carefully documented so that differences in the exposures and efficacy of treatment can be evaluated and collated.

TABLE 7.20—*Chelating Drug DTPA*

Compound	Route of Administration and Dose	Remarks
CaDTPA (trisodium calcium pentathamil, Ditripentat (Heyl & Co., Berlin))		Drug is available in the U.S. only as an investigational new drug from the U.S. Department of Energy, Office of Health and Environmental Research, Human Health and Assessment Division, Washington, D.C. or REAC/TS Center, Oak Ridge, Tennessee.
	Intravenous Adults—1 g in 250 ml normal saline or 5 percent glucose in water. Infuse over 1 hour. Infusion may be repeated on 5 successive days per week.	Give in a single daily dose. Do not give in divided or protracted doses. CAUTIONS: (1) Drug is contraindicated in minors and if significant leukopenia or thrombocytopenia exists. (2) Kidney function should be normal. Urinalysis should be normal prior to each use. If proteinuria, blood, or casts are present, discontinue drug administrations. (3) Check blood pressure during infusion. (4) Discontinue drug if diarrhea occurs. (5) See discussion in text on potential toxicity to fetuses.
	Aerosol Inhalant Adults—1 g in 4 ml vial is placed in nebulizer. Entire volume usually inhaled 15–30 minutes. Inhalation administration can be repeated daily, or if indicated, 2 to 3 times per week.	This route of administration is not covered in the current IND permit for CaDTPA, but has been used safely in humans. Do not use this method in persons with pre-existing pulmonary disease.
ZnDTPA (trisodium zinc pentathamil)	Same dose as CaDTPA for intravenous or aerosol administration daily.	Less toxic than CaDTPA and is the preferred form of DTPA except in the first day or two after exposure when CaDTPA is somewhat more effective. Available as an investigational new drug as described for CaDTPA above.

No serious toxicity in man has been reported as a result of CaDTPA administrations in recommended doses. When given repeatedly, with short intervals for recovery, CaDTPA treatment in man may cause nausea, vomiting, diarrhea, chills, fever, pruritus, and muscle cramps in the first 24 hours (Constantoulakis *et al.*, 1974; Seven and Johnson, 1960). Over longer time periods, depletion of zinc due to CaDTPA therapy has resulted in transient inhibition of a metalloenzyme, β-aminolevulinic acid dehydratase (ALAD), in the blood although without observable clinical effect (Cohen *et al.*, 1976). Anosmia was observed in one individual after 123 g of CaDTPA over twenty-seven

months of therapy (Poda, 1979; Jolley *et al.*, 1972) and possibly could have been related to zinc depletion. After 100 days of no further DTPA administration, the patient's sense of smell began to return.

Studies in animals indicate that the toxicity of CaDTPA depends on the total dose and the dose schedule (Planas-Bohne and Ebel, 1975). When administered to animals in high doses (≥2000 μmol/kg—clinical dose range is 10-30 μmol/kg), it can produce severe lesions of the kidneys, intestinal mucosa, and liver, and be lethal (Planas-Bohne and Lohbreier, 1976). Increased toxicity from fractionated dose schedules has been demonstrated in dog experiments in which injections at human dose levels, 5.8 μmol/kg of CaDTPA given every 5 hours, were fatal as early as four days after the onset of treatment (Taylor *et al.*, 1974). The most significant injury occurs in the intestinal epithelium. In rats, continuous infusion of similar total doses per day caused death in 8-14 days (Sullivan *et al.*, 1974), but the same dose given as a single daily injection failed to elicit this response (Planas-Bohne and Ebel, 1975). Toxicity in these cases apparently resulted from depletion of the Zn and Mn ions needed in the enzymatic steps leading to DNA synthesis that renews the cells in the intestinal epithelium (Gabard, 1974). No untoward effects in rats were noted with doses of 100 μmol CaDTPA/kg given twice weekly and apparently there was no influence on Zn or Mn concentrations over a 44-week period (Planas-Bohne and Lohbrier, 1976). Long-term, low dose CaDTPA administrations in man, 1 g per week, showed no adverse effects after 4 years of such administrations (Slobodien *et al.*, 1973). Urinary zinc excretion studies suggest that the zinc supply is quickly replenished under this treatment regimen and that any partial depletion of the zinc-stores, if it occurs at all, would be transient.

Teratogenicity and fetal death have occurred in mice following five daily injections of 720-2880 μmol CaDTPA/kg given throughout gestation (Fisher *et al.*, 1975; 1976). However, daily doses of 360 μmol CaDTPA/kg in mice, about 10 times the daily human dose, produced no harmful effects (Fisher *et al.*, 1975). On the basis of these results and the lesser daily intake of zinc by humans compared to rats and mice, it has been postulated that the toxic effects on the human fetus might occur at the recommended daily dose levels of about 30 μmol CaDTPA/kg (Mays *et al.*, 1976). In the same experiments ZnDTPA did not give similar toxicity. Studies of 2 pregnant beagles given daily injections of CaDTPA at 30 μmol/kg, a daily dose comparable to 1 g in a 70 kg man, starting at 15 days of gestation until the end of pregnancy, have shown severe effects (especially brain damage) on the fetuses (Mays *et al.*, 1977).

To summarize the toxicity reactions from CaDTPA: (1) No serious

adverse reactions have been reported in man from its use in hundreds of treatments at the recommended doses and treatment schedules; (2) fractionation of the daily dose (several smaller doses per day) is contraindicated; (3) it is doubtful that a single or several well-spaced doses of CaDTPA would be harmful to pregnant females or fetuses, especially if supplemental zinc (220 mg zinc sulfate tablets daily delivers 50 mg zinc) is given as a prophylactic measure, but ZnDTPA is preferred in this circumstance and should be used if available; (4) where there is known pre-existing serious kidney disease or depressed myelopoietic function (e.g., pathologic leukopenia or thrombocytopenia), CaDTPA treatment is contraindicated; and (5) in prolonged treatment regimens, the ZnDTPA is preferred to CaDTPA because of its lesser toxicity.

Inhalation of an aerosol of CaDTPA has been used as a convenient method of administration of the drug and has the advantage of good patient acceptance. No serious adverse reactions have been reported from this form of administration. In one case, symptoms of chills, fever, thirst, diuresis, myalgia, headaches, and paresthesias began about eight hours after aerosol administration of 1 g CaDTPA and lasted about four to five hours (Lincoln, 1976). Animal experiments have shown no persistent effects from aerosol administration of CaDTPA although a transitory vesicular emphysema of less than 3 weeks duration was reported in rats and hamsters (Smith *et al.*, 1976). Similar pathology was seen also in the control animals, but the finding was stated to be statistically increased in the DTPA treated animals. The amount of DTPA absorbed by this route of administration has not been measured, but generally it has had about the same therapeutic effectiveness as intravenous or intramuscular administrations (Smith *et al.*, 1976; Nenot *et al.*, 1971). Stather *et al.* (1976) reported that an aerosol of CaDTPA given soon after exposure was significantly more effective than intravenous CaDTPA in removing the pulmonary deposits of soluble forms of plutonium. The residence time of inhaled CaDTPA in the body appears to be increased by at least a factor of two compared to intravenous administration (Smith, 1974).

Summary of the experience to date on inhalation of CaDTPA suggests: (1) Aerosol administrations generated from 1 g of CaDTPA given daily for a few days appear to have no serious effects in man; (2) if pre-existing lung pathology is known to be present, it is prudent not to use the inhalation route; and (3) the main advantage of inhaled CaDTPA over the intravenous route appears to be patient convenience and ease of administration, although increased therapeutic effectiveness has been noted in some experimental animal studies. If inhaled CaDTPA treatment offers therapeutic advantages, they are most likely

to be seen when it is used immediately after inhalation of soluble forms of plutonium. Aerosol inhalations of ZnDTPA is an approved method of administration in the IND protocol. One person has reported a metallic taste and sore throat following ZnDTPA aerosol administrations (Poda, 1979). This has not been reported with CaDTPA.

7.3.5.4 *Dimercaprol.* (See Table 7.21). Dimercaprol (BAL) forms stable chelates with mercury, lead, arsenic, gold, bismuth, chromium, and nickel. It therefore may be considered for the treatment of internal contamination with the radioisotopes of these elements. This chelating agent competes with endogenous sulfhydryl groups for those metals more attracted to $-SH$ groups than to $-O^-$. It complements the action of the polyaminocarboxylic acid family of chelators, e.g., EDTA, which attach to metals through $-O^-$ or $-N^-$. While seldom the agent of first choice, dimercaprol usually is available in the pharmacy and should be useful in accelerating removal of the ions of the metals listed above that are attached to the $-S^-$ structure. Unfortunately, dimercaprol is toxic and therefore the hazards of its use have to be carefully balanced against any benefits it may have in accelerating excretion and preventing tissue uptake.

Approximately 50 percent of subjects receiving 6 mg/kg intramuscularly will experience toxicity reactions (Levine, 1975). There is frequently a rise in both systolic and diastolic blood pressure accompanied by tachycardia. Nausea, vomiting, headache, a burning sensation in the mouth, conjunctivitis, chest pain, and a general feeling of anxiety are unpleasant but not dangerous reactions. Painful sterile abscesses occasionally develop at the sites of injection. Excretion of essential trace metals such as zinc and manganese may be increased but it is considerably less than occurs with EDTA, DTPA, or penicillamine. Metal complexes with dimercaprol tend to break down in acid media and some metals, such as mercury and zinc, can be left behind in the epithelium of the renal tubule. The maintenance of an alkaline urine can help protect the kidney (Goodman and Gilman, 1975).

Dimercaprol has proved to be an effective drug in the treatment of acute inorganic mercury poisoning (Longcope and Luetscher, 1949), but is less effective for chronic mercury poisoning. It would appear to be a useful chelating agent following exposures to large amounts of ^{203}Hg or ^{197}Hg. Penicillamine and CaEDTA appear to be more effective in treating chronic mercury poisoning (Kark *et al.*, 1971), and since they are less toxic, they would probably be preferred for the treatment of radiomercury uptake.

7.3.5.5 *Penicillamine.* (See Table 7.22). Penicillamine is an amino acid derived from the degradation of penicillin, but it is devoid of antibacterial activity. It chelates with copper, iron, mercury, lead, gold, and possibly other heavy metals to form soluble complexes that are

TABLE 7.21—*Dimercaprol*

Compound	Route of Administration and Dose	Remarks
Dimercaprol (BAL in oil, British Anti-Lewisite, 2,3-dimercapto-1-propanol)	*Intramuscular* 2.5 mg/kg or less administered at 4-hour intervals during the first 2 days, twice on the third day and once daily for 5–10 days (Levine, 1975).	Larger or smaller amounts may be given depending on the level of exposure. These doses are based on treatment of intoxication with stable arsenic and gold. The high toxicity of this drug should be taken into consideration before use.

excreted in the urine. It is superior to dimercaprol and CaEDTA for removal of copper. The primary use of penicillamine has been to remove excess copper from patients with hepatolenticular degeneration (Wilson's Disease) (Walshe, 1967). In such cases there are no contraindications to its use since Wilson's Disease is usually progressive and eventually fatal. It has also been used to treat lead poisoning (Boyd *et al.*, 1957) and to increase mercury clearance (Krishnamurthy *et al.*, 1970).

The incidence of adverse effects with penicillamine is low; reactions are most likely to occur shortly after beginning therapy. Penicillamine is less toxic than dimercaprol. The most common and serious reactions are hypersensitivity reactions manifested by a maculopapular or erythematous rash. The rash occasionally is accompanied by fever, leukopenia, thrombocytopenia, eosinophilia, arthralgia, or lymphadenopathy. One fatal case of granulocytopenia has been reported. Purpuric and vesicular ecchymoses are seen occasionally, but are not progressive and discontinuation of therapy is usually not necessary. Other reported adverse effects include thrombophlebitis, cheilosis, and the nephrotic syndrome (American Medical Association, 1977).

In light of present knowledge, penicillamine does not appear to be an especially promising drug for treatment of internal radionuclides. Penicillamine added to the food of rats (50 mg/day or equivalent to 270 mg/kg of body weight) beginning 12 hours after oral administration of ^{198}Au, ^{203}Hg, and ^{210}Pb resulted in shortened biological half-times for each (Silva *et al.*, 1973). The effectiveness of treatment, judged by the integrated radiation dose to the body, showed that the control animals received about 1.4 to 1.5 times the radiation compared to the treated animals over a period of 60 days. Exposure to radioactive copper (^{64}Cu) might be an indication for this drug, but the 13-hour half-life is so short that it is unlikely that the drug would enhance excretion sufficiently over only a few days to be of practical value.

7.3.5.6 *Deferoxamine.* (See Table 7.23). Deferoxamine (DFOA; also desferrioxamine) has been effective in the treatment of iron storage

TABLE 7.22—*Penicillamine*

Compound	Route of Administration and Dose	Remarks
Penicillamine (Cuprimine, D-3-mercaptovaline)	*Oral* Adult, 250 mg four times daily. May be increased to 4 or 5 g daily in divided doses. Take on empty stomach between meals and at bedtime.	Take blood cell counts and urinalysis every three days during first two weeks of therapy, and at least every 10 days thereafter. Give cautiously if person has pencillin sensitivity. If adverse reaction occurs, discontinue the drug until it subsides.

diseases (Thompson *et al.*, 1967; Smith, 1964a) and acute iron poisoning (Jacobs *et al.*, 1965). The primary affinity of DFOA is for iron in the ferric (trivalent) state. It has low affinity for ferrous (bivalent) iron and other bivalent metals.

Combining DFOA and DTPA increases the total effectiveness of iron chelation because intracellular iron stores are the site of action of DFOA, while DTPA chelates only extracellular iron in transit in the serum (Hershko, 1975). Rapid urinary excretion of absorbed iron occurs after intravenous administration of DFOA. Oral DFOA can be used advantageously following inhalation or ingestion of ^{59}Fe since it binds the iron in the lumen of the bowel and renders it non-absorbable (Levine, 1975). Normally up to about 15 percent of ingested iron is absorbed.

DFOA equals or surpasses CaDPTA in enhancing the excretion of plutonium (IV) compounds provided the drug is given promptly (Rosenthal and Lindenbaum, 1964; Smith, 1964b; Taylor, 1967; Volf, 1975; 1976; Volf *et al.*, 1977). Its usefulness in the clinical situation may be questioned because its effectiveness declines rapidly, possibly due to metabolic degradation (Catsch and Harmuth-Hoene, 1975). DFOA also causes increased retention of plutonium by the kidney.

The combination of DFOA and CaDTPA yields better results than either drug separately in the treatment of plutonium poisoning. This combination also eliminates the kidney retention seen with DFOA alone (Volf *et al.*, 1977). Volf (1976) estimates that 0.4 g CaDTPA plus 0.5 g DFOA would achieve an excretion of incorporated ^{239}Pu equivalent to 1 g CaDTPA alone or 0.7 g DFOA alone. In rats, DFOA has decreased bone deposition of ^{239}Pu to about one-half the value when CaDTPA was used alone. This effect is probably the result of different sites of action of DFOA and possible accessibility to metabolic compartments denied to CaDTPA (Smith, 1964b) and to the possible formation of mixed ligand complexes (Volf, 1975; Catsch and Harmuth-Hoene, 1975; Schubert, 1972).

While DFOA shows promise for removal of plutonium, it has not

TABLE 7.23—*Deferoxamine*

Compound	Route of Administration and Dose	Remarks
Deferoxamine (Desferal, desferrioxamine)	*Intramuscular* 1 g initially, followed by 500 mg every four hours for two doses. Depending upon clinical response, 500 mg then given every 4 to 12 hours to maximal total dosage of 6 g in 24 hours. 500 mg/day may be given daily for as long as 10 days (Constantoulakis *et al.*, 1974). *Oral* Up to 8 g may be given orally by nasogastric tube when prevention of uptake from the gut is desired (Levine, 1975). *Intravenous* Same as IM dose. Rate of IV infusion should never exceed 15 mg/kg of body weight/hour.	See toxic reactions in text below and read drug insert. The doses given are based on treatment of intoxication with stable iron.

been approved by the FDA for this purpose. DFOA alone or in combination with CaDTPA can be used for accidental excessive uptake of ^{59}Fe.

Although intramuscular administraton of DFOA is preferred for treating iron poisoning, the most successful regimen for severe iron poisoning is intravenous infusion of DFOA with exchange transfusions as necessary. Toxic reactions, usually manifested as a generalized erythema, flushing, tachycardia, urticaria, or sudden hypotension, are serious enough to contraindicate its further use in treatment of mild iron poisoning.

7.4. Lung Lavage

Lavage of the tracheobronchial tree has shown promise as a technique for treating individuals who have accidentally inhaled relatively insoluble radionuclides (Pfleger *et al.*, 1969a; 1969b). A bronchopulmonary lavage technique has been used by Kylstra *et al.* (1971) to remove inflammatory exudates and other foreign materials from the lungs of humans suffering from a variety of chronic obstructive lung diseases. The procedure requires a general anesthetic for the placement

of a double lumen endotracheal tube with two cuffs. Inflation of the cuffs, one in the trachea and the other in a main bronchus, isolates the right lung from the left lung. The entire volume of one lung is then filled with isotonic saline, or other irrigation fluid. The lung is filled and drained repeatedly by gravity flow. At the end of the procedure as much fluid as possible is removed from the treated lung by drainage followed by suction.

The use of lung lavage for removal of inhaled radioactive aerosols has been studied experimentally in dogs and baboons. Dogs were lavaged after inhalation of ^{144}Ce, ^{137}Cs, or ^{95}Zr-^{95}Nb in insoluble fused clay particles (Pfleger *et al.*, 1969b; Boecker *et al.*, 1974; Muggenburg *et al.*, 1975). A single lavage of one lung will remove about 12 percent of the initial lung burden, while lavage of both lungs will remove about twice that value (Muggenburg *et al.*, 1977). An initial lung burden may be reduced about 25 to 50 percent (average was 44 percent in eight dogs) by means of 10 saline lavage treatments, five for each lung. Each lung was lavaged once each week during the first two weeks after exposure followed by lavage of alternate lungs each week out to 56 days. A 53 percent reduction of cumulative radiation dose to the lung resulted from these treatments; radiation pneumonitis and early deaths were prevented in the majority (75 percent) of the treated dogs in contrast to the untreated dogs (Muggenburg *et al.*, 1975). After inhalation of ^{239}Pu and ^{238}Pu polydisperse aerosols having different chemical characteristics, the same regimen of 10 lavages removed 35 to 49 percent of the initial lung burdens in all dogs except one, which had only an 18 percent removal (Muggenburg *et al.*, 1976a). In baboons exposed by inhalation of plutonium oxide, treatment with 10 pulmonary lavages resulted in removal of 60 to 90 percent of their lung burdens (Nolibé *et al.*, 1976).

Additional experiments in dogs indicated that 10 lavage treatments within 24 days gave approximately the same results as 10 lavages in 56 days (Silbaugh *et al.*, 1975). Ten more lavages (20 total) removed an average of 52 percent of the initial lung burden, a total amount that was not greatly different from results of the original 10 lavage schedule. Studies on ^{144}Ce in insoluble fused clay particles indicate that a sizable percentage (over 80 percent) of the insoluble particles in the lung continued to be accessible to removal by bronchopulmonary lavage for periods up to 6 months after exposure, but translocation from the lungs to other tissues does increase with time (Felicetti *et al.*, 1975). Thus, although early treatment is desirable when the deposited radionuclide(s) has a high dose rate, the time after exposure that lung lavage treatments are initiated may not be critical, up to several

months after exposure, for the removal of material with a long lung retention time (Muggenburg *et al.*, 1977).

In one human case of an inhaled ^{239}Pu aerosol, three lavages (8, 12, and 17 days post exposure) removed about 13 percent of the estimated initial lung burden (McClellan *et al.*, 1972). The aerosol proved more soluble than was assumed initially and this factor may have reduced the effectiveness of lavage therapy. The excretion of ^{239}Pu in the urine following daily intravenous administration of CaDTPA, starting on day 8 after exposure, was about 17 percent of the initial lung burden. Muggenburg *et al.* (1977) point out that lavage and chelation therapy can be used effectively together for heterogeneous aerosols.

Possible use of this technique in man requires a careful risk-benefit assessment. The risk of the procedure lies with both the administration of a general anesthetic and any mortality or morbidity that could be associated with the procedure. Muggenburg *et al.* (1972) found that dogs serially sacrificed after lavage had no physiologic or pathologic changes one week after the procedure. Early physiologic alterations were resolved within 24 hours and only vestiges of tissue reaction were found by light microscopy at 48 hours. After three lavages of the man exposed to plutonium there was no evidence of impaired lung function or signs of adverse reactions 24 hours after the last procedure. Studies of surfactant lipids in the lungs of dogs show that the lipids removed by lavage are replaced in about five hours (Henderson *et al.*, 1975). Muggenburg *et al.* (1976b) have shown in dogs that multiple lung lavages carry little biomedical risk and that the primary risk is associated with general anesthesia.

In a review of clinical and experimental uses of bronchopulmonary lavage (Muggenburg and Jones, 1971), it was noted that one death was recorded after 204 lavages in 70 patients who had various types of severe obstructive lung disease. In dogs two deaths were recorded after 420 lavages in 149 animals. An update on humans cites one death after 258 lavages in 112 persons (Muggenburg *et al.*, 1976a). Nolibé *et al.* (1976) report 5 deaths in baboons in the course of 800 lavages. This overall experience suggests a possible mortality rate of approximately 0.5 percent for each lavage procedure. Since the human cases were complicated by the presence of debilitating pulmonary disorders, the estimated risk is probably greater than is to be expected in normal individuals.

Because lavage requires general anesthesia the risks should also be related to the general experience with low risk surgical procedures. In the National Halothane Study (NAS/NRC, 1969) the low death rate operations (such as mouth and dental procedures, all eye surgery,

herniorrhaphy, D & C, hysterectomy, cystoscopy, and plastic skin surgery) on persons age 10 to 49 years, who were in the two best physical conditions categories, had a mortality rate of about 0.05 percent or 1 per 2000 cases. The average for all low death rate operations was 0.23 percent or 1 per 435 cases. Endoscopy of the trachea, esophagus, and larynx of patients 10 to 49 years of age in good condition resulted in a mortality rate that ranged from 0.08 to 0.85 percent and was categorized with the middle death rate cases. Endoscopy is the procedure most similar to a bronchopulmonary lavage.

An additional significant consideration is that the risk from the lavage procedure is immediate, while the potential effects from internal radioactive emitters is 10, 20, or more years in the future unless the exposure is so high as to cause acute radiation damage. Deliberations on the justification of the procedure should consider the age and health of the patient relative to the possible deleterious effects of the radiation exposure (see Section 5.2). There is no ideal means of determining this. Exposures that carry a risk of acute or subacute radiation effects should be considered as potential candidates for lavage.

APPENDIX A

Interagency Radiological Assistance Plan (IRAP)

In accordance with the Interagency Radiological Assistance Plan (IRAP), the U.S. Department of Energy (DOE) is responsible for the implementation of the IRAP through a national coordinating office and regional coordinating offices (RCO's) (ERDA, 1975). Through this organization, DOE will make available radiological advice and assistance as may be appropriate to minimize injury to people, to minimize loss of property, to cope with radiological hazards, and to protect the public health and safety. Assistance is dispatched whenever an RCO or the DOE National Coordinating Office believes that such action is necessary, or in response to a request from DOE contractors, licensees, federal, state, and local agencies, private organizations, or private persons. One of the prime objectives is to develop and maintain an emergency radiological assistance capability that will be able to respond 24 hours a day for the protection of the health and safety of the public, of persons employed in DOE work, and of others whose health or safety may be endangered as the result of radiological incidents. Incidents that qualify for radiological advice and assistance are defined in the DOE Radiological Assistance Plan as those "believed to involve source, by-product, or special nuclear material—or other ionizing radiation sources—used in DOE-supported work." Radium and other naturally-occurring radionuclides and particle accelerators are included in "other ionizing radiation sources" used in DOE-supported work.

The DOE and several of the federal agencies signatory to the IRAP have established and trained emergency response teams that are expertly staffed and appropriately equipped to conduct offsite radiological emergency operations. Assistance can range from expert technical advice on the telephone to the dispatch of an emergency team or a single expert to the scene. The radiological assistance team is prepared to give advice on and, if necessary, to perform those radiological emergency operations that appear to be needed immediately to

save life, to minimize personal injury, to protect the public from exposure to radioactive materials, to control radiological hazards, and to protect property and the environment from radioactive contamination. If requested by the injured individual or his physician, a radiological assistance team physician may give advice regarding hospitalization and further definitive treatment. At the request of a patient or his physician, medical advice and consultation are available through DOE from physicians specializing in the treatment of radiation expo-

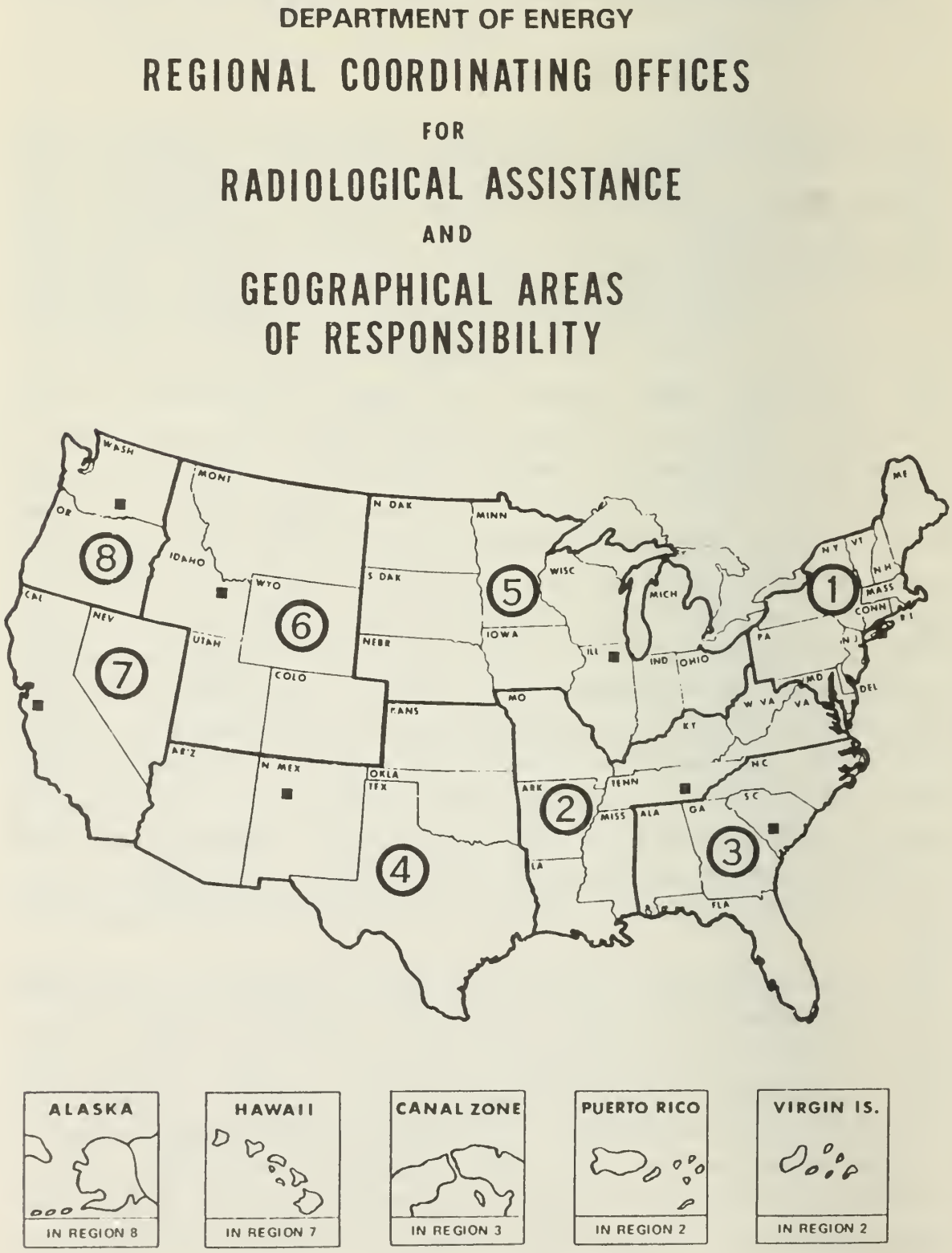

Fig. A.1.a. Department of Energy Regions.

	REGIONAL COORDINATING OFFICE	POST OFFICE ADDRESS	TELEPHONE for ASSISTANCE
1	BROOKHAVEN AREA OFFICE	UPTON, L. I. NEW YORK 11973	(516) 345-2200
2	OAK RIDGE OPERATIONS OFFICE	P. O. BOX E OAK RIDGE, TENNESSEE 37830	(615) 576-1005 or (615) 525-7885
3	SAVANNAH RIVER OPERATIONS OFFICE	P. O. BOX A AIKEN, S. C. 29801	(803) 725 3333
4	ALBUQUERQUE OPERATIONS OFFICE	P. O. BOX 5400 ALBUQUERQUE, NEW MEXICO 87115	(505) 264-4667
5	CHICAGO OPERATIONS OFFICE	9800 S. CASS AVE. ARGONNE, ILLINOIS 60439	(312) 972-4800 Duty Hrs. -5731 Off Hrs.
6	IDAHO OPERATIONS OFFICE	P. O. BOX 2108 IDAHO FALLS, IDAHO 83401	(208) 526-1515
7	SAN FRANCISCO OPERATIONS OFFICE	1333 BROADWAY OAKLAND CALIFORNIA 94612	(415) 273-4237
8	RICHLAND OPERATIONS OFFICE	P. O. BOX 550 RICHLAND, WASHINGTON 99352	(509) 942-7381

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Fig. A.1.b. DOE Regional Coordinating Offices

sure cases, and special medical facilities, that are not otherwise available to the patient or his physician, may be made available for the diagnosis and treatment of radiation injury.

Request for radiological assistance for incidents involving radioactive material can be made by contacting the Department of Energy through one of its regional offices as shown in Figure A-1. Through this single contact, the resources of 13 federal agencies applicable to radiological emergencies are made available under the IRAP.

APPENDIX B

Definitions

absorbed dose: When ionizing radiation passes through matter, some of its energy is imparted to the matter. The amount absorbed per unit mass of irradiated material is called the absorbed dose. The special unit of absorbed dose is the rad.

activity: The number of nuclear transformations occurring in a given quantity of material per unit time. The special unit of activity is the curie.

alpha particle: A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons bound together, and hence is identical with the nucleus of a helium atom. It is the least penetrating of the three common types of radiation (alpha, beta, gamma) emitted by radioactive materials, and is stopped by a sheet of paper.

Anger camera: A highly collimated gamma detector used for radioactivity scans in nuclear medicine.

beta particle: An elementary particle emitted from a nucleus during radioactive decay, having a single electrical charge and a mass equal to 1/1837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is called a positron.

biological half-time: The time required for a biological system to eliminate, by natural processes, half the amount of a substance (e.g., radioactive material) that has entered it.

contamination (radioactive): A radioactive substance dispersed in materials or places where it is undesirable.

criticality: A term used in weapon and reactor physics to describe the state of a given fission system when the specified conditions are such that the mass of active material present is precisely a critical mass. Thus, the fission neutron production rate is a constant and is exactly balanced by the combined rate of neutron loss and utilization so that the neutron population remains a constant. Supercriticality occurs when a greater than critical mass of active material is present and the neutron population increases rapidly.

curie: The special unit of activity. (1) One curie equals 3.7×10^{10}

nuclear transformations per second. (2) By popular usage, the quantity of any radioactive material having an activity of one curie.

daughter, daughter product: A nuclide, stable or radioactive, formed by radioactive decay of another nuclide, which in this context is called the parent.

decontamination: The removal of radioactive contaminants from surfaces (e.g., skin) by cleaning and washing.

effective half-life (T_{eff}): The time required for a radionuclide contained in a biological system, such as in man, to reduce its activity by half, as a combined result of radioactive decay and biological elimination.

electron volt (eV): A unit of energy equal to the kinetic energy gained in a vacuum by a particle having one electronic charge when it passes through a potential difference of 1 volt; 1 eV = 1.60×10^{-19} J.

fission products: The nuclei (fission fragments) formed by the fission of heavy elements, plus the nuclides formed by the fission fragments' radioactive decay.

gamma rays: High-energy, short-wavelength electromagnetic radiation. Gamma radiation frequently accompanies alpha and beta emissions and always accompanies fission. Gamma rays are very penetrating and are best stopped or shielded against by dense materials, such as lead or depleted uranium. Gamma rays are essentially similar to x rays, but are usually more energetic, and are nuclear in origin.

Geiger-Mueller (GM) Counter: A radiation detection and measuring instrument. It consists of a gas-filled (Geiger-Mueller) tube containing electrodes, between which there is an electrical voltage but no current flowing. When ionizing radiation passes through the tube, a short intense pulse of current passes from the negative electrode to the positive electrode and is measured or counted. The number of pulses per second measures the intensity of radiation. It is also often known as a Geiger counter; it was named for Hans Geiger and W. Mueller who invented it in the 1920's.

health physics: The science concerned with recognition, evaluation, and control of health hazards from ionizing radiation.

ionization chamber: An instrument that detects and measures ionizing radiation by measuring the electrical current that flows when radiation ionizes gas in a chamber, making the gas a conductor of the electricity.

ionizing radiation: Any radiation displacing electrons from atoms or molecules, thereby producing ions.

isotopes: One of two or more atoms with the same atomic number (the same chemical element) but with different atomic weights. An

equivalent statement is that the nuclei of isotopes have the same number of protons but different numbers of neutrons. Isotopes usually have very nearly the same chemical properties, but somewhat different physical properties.

kilo electron volts (keV): 1,000 eV.

linear energy transfer (LET): A measure of the ability of biological material to absorb ionizing radiation; the radiation energy lost per unit length of path through a biological material. In general, the higher the LET value, the greater is the relative biological effectiveness of the radiation in that material.

maximum permissible body burden: That quantity of activity of a specific radioactive material that may be present in a worker's body continually for a working lifetime and result in the maximum permissible dose.

microcurie (μCi): A one millionth part of a curie or 3.7×10^4 nuclear transformations per second.

milliroentgen (mR): A one-thousandth part of a roentgen.

million electron volts (MeV): 1,000,000 eV.

nanocurie (nCi): A one billionth (10^{-9}) part of a curie or 37 nuclear transformations per second.

neutron: An uncharged elementary particle with a mass slightly greater than that of the proton and found in the nucleus of every atom heavier than hydrogen. A free neutron is unstable and decays with a half-life of about 13 minutes into an electron, proton, and neutrino. Neutrons sustain the fission chain reaction in a nuclear reactor.

nonpenetrating radiation: A general term used to describe external radiations of such low penetrating power that the absorbed dose from exposures to man is principally in the skin and does not reach deeper organs to any significant extent. It refers to alpha, beta, and very soft gamma or x-ray radiations.

nuclide: A general term applicable to all atomic forms of the elements. The term is often erroneously used as a synonym for "isotope," which properly has a more limited definition. Whereas isotopes are the various forms of a single element (hence are a family of nuclides) and all have the same atomic members, nuclides comprise all the isotopic forms of all the elements.

penetrating radiation: A general term used to describe external radiations with sufficient penetrating power that the absorbed dose from exposures to man is delivered in significant quantities to tissues and organs other than the skin. It refers to gamma, x, and neutron radiations.

physical half-life: The time required for a radioactive substance to

lose 50 percent of its activity by decay. It is the radioactive half-life.

picocurie (pCi): A one trillionth (10^{-12}) part of a curie or 0.037 nuclear transformations per second.

proton: An elementary particle with a single positive electrical charge and a mass approximately 1837 times that of the electron. The nucleus of an ordinary or light hydrogen atom. Protons are constituents of all nuclei. The atomic number (Z) of an atom is equal to the number of protons in its nucleus.

rad: The special unit of absorbed dose. A dose of one rad means the absorption of 100 ergs of radiation energy per gram of absorbing material or 10^{-2} joules per kilogram of absorbing material.

radioactivity: The spontaneous decay or disintegration of an unstable atomic nucleus, usually accompanied by the emission of ionizing radiation. See activity.

radionuclide: A radioactive nuclide.

relative biological effectiveness: A factor used to compare the biological effectiveness of different types of ionizing radiation. It is the inverse ratio of the amount of absorbed radiation, required to produce a given effect, to a standard or reference radiation required to produce the same effect.

rem: The special unit of dose equivalent. The dose equivalent in rems is numerically equal to the absorbed dose in rads multipled by the quality factor, the distribution factor, and any other necessary modifying factors.

roentgen (R): The special unit of exposure. One roentgen equals 2.58×10^{-4} Coulomb per kilogram of air.

x ray: A penetrating form of electromagnetic radiation emitted either when the inner orbital electrons of an excited atom return to their normal state or when a metal target is bombarded with high-speed electrons. X rays are always nonnuclear in origin.

whole-body counter: A device used to identify and measure the radioactivity in the body (body burden) of human beings and animals; it uses heavy shielding to keep out background radiation and measures the body burden with ultrasensitive scintillation detectors and electronic equipment.

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The National Council on Radiation Protection and Measurements is a nonprofit corporation chartered by Congress in 1964 to:

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3. Develop basic concepts about radiation quantities, units, and measurements, about the application of these concepts, and about radiation protection;
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SC-46: Operational Radiation Safety
SC-47: Instrumentation for the Determination of Dose Equivalent
SC-48: Apportionment of Radiation Exposure
SC-51: Radiation Protection in Pediatric Radiology and Nuclear Medicine Applied to Children
SC-52: Conceptual Basis of Calculations of Dose Distributions
SC-53: Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Radiation
SC-54: Bioassay for Assessment of Control of Intake of Radionuclides
SC-55: Experimental Verification of Internal Dosimetry Calculations
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In recognition of its responsibility to facilitate and stimulate cooperation among organizations concerned with the scientific and related aspects of radiation protection and measurement, the Council has created a category of NCRP Collaborating Organizations. Organizations or groups of organizations that are national or international in scope and are concerned with scientific problems involving radiation quantities, units, measurements and effects, or radiation protection may be admitted to collaborating status by the Council. The present Collaborating Organizations with which the NCRP maintains liaison are as follows:

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American College of Radiology
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American Industrial Hygiene Association
American Insurance Association
American Medical Association
American Nuclear Society
American Occupational Medical Association
American Podiatry Association
American Public Health Association
American Radium Society
American Roentgen Ray Society
American Society of Radiologic Technologists
American Society of Therapeutic Radiologists
Association of University Radiologists
Atomic Industrial Forum
College of American Pathologists
Federal Emergency Management Agency
Genetics Society of America
Health Physics Society
National Bureau of Standards
National Electrical Manufacturers Association
Radiation Research Society
Radiological Society of North America
Society of Nuclear Medicine
United States Air Force
United States Army
United States Department of Energy
United States Department of Labor
United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission
United States Public Health Service

The NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

The Council's activities are made possible by the voluntary contribution of the time and effort of its members and participants and the generous support of the following organizations:

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To all of these organizations the Council expresses its profound appreciation for their support.

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The NCRP seeks to promulgate information and recommendations based on leading scientific judgment on matters of radiation protection and measurement and to foster cooperation among organizations concerned with these matters. These efforts are intended to serve the public interest and the Council welcomes comments and suggestions on its reports or activities from those interested in its work.

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Lauriston S. Taylor Lectures

No.	Title and Author
1	*The Squares of the Natural Numbers in Radiation Protection* by Herbert M. Parker
2	*Why be Quantitative About Radiation Risk Estimates?* by Sir Edward Pochin
3	*Radiation Protection-Concepts and Trade Offs* by Hymer L. Friedell

NCRP Reports

No.	Title
8	*Control and Removal of Radioactive Contamination in Laboratories* (1951)
9	*Recommendations for Waste Disposal of Phosphorus-32 and Iodine-131 for Medical Users* (1951)
12	*Recommendations for the Disposal of Carbon-14 Wastes* (1953)
16	*Radioactive Waste Disposal in the Ocean* (1954)
22	*Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (1959) [Includes Addendum 1 issued in August 1963]
23	*Measurement of Neutron Flux and Spectra for Physical and Biological Applications* (1960)
25	*Measurement of Absorbed Dose of Neutrons and of Mixtures of Neutrons and Gamma Rays* (1961)
27	*Stopping Powers for Use with Cavity Chambers* (1961)
30	*Safe Handling of Radioactive Materials* (1964)
32	*Radiation Protection in Educational Institutions* (1966)

33 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Equipment Design and Use* (1968)
35 *Dental X-ray Protection* (1970)
36 *Radiation Protection in Veterinary Medicine* (1970)
37 *Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides* (1970)
38 *Protection against Neutron Radiation* (1971)
39 *Basic Radiation Protection Criteria* (1971)
40 *Protection Against Radiation From Brachytherapy Sources* (1972)
41 *Specification of Gamma-Ray Brachytherapy Sources* (1974)
42 *Radiological Factors Affecting Decision-Making in a Nuclear Attack* (1974)
43 *Review of the Current State of Radiation Protection Philosophy* (1975)
44 *Krypton-85 in the Atmosphere—Accumulation, Biological Significance, and Control Technology* (1975)
45 *Natural Background Radiation in the United States* (1975)
46 *Alpha-Emitting Particles in Lungs* (1975)
47 *Tritium Measurement Techniques* (1976)
48 *Radiation Protection for Medical and Allied Health Personnel* (1976)
49 *Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV* (1976)
50 *Environmental Radiation Measurements* (1976)
51 *Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities* (1977)
52 *Cesium-137 From the Environment to Man: Metabolism and Dose* (1977)
53 *Review of NCRP Radiation Dose Limit for Embryo and Fetus in Occupationally-Exposed Women* (1977)
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1	*X-Ray Protection* (1931). [Superseded by NCRP Report No. 3]
2	*Radium Protection* (1934). [Superseded by NCRP Report No. 4]
3	*X-Ray Protection* (1936). [Superseded by NCRP Report No. 6]
4	*Radium Protection* (1938). [Superseded by NCRP Report No. 13]
5	*Safe Handling of Radioactive Luminous Compounds* (1941). [Out of print]
6	*Medical X-Ray Protection up to Two Million Volts* (1949). [Superseded by NCRP Report No. 18]
7	*Safe Handling of Radioactive Isotopes* (1949). [Superseded by NCRP Report No. 30]
10	*Radiological Monitoring Methods and Instruments* (1952). [Superseded by NCRP Report No. 57]
11	*Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (1953). [Superseded by NCRP Report No. 22]
13	*Protection Against Radiations from Radium, Cobalt-60 and Cesium-137* (1954). [Superseded by NCRP Report No. 24]
14	*Protection Against Betatron—Synchrotron Radiations Up to 100 Million Electron Volts* (1954). [Superseded by NCRP Report No. 51]
15	*Safe Handling of Cadavers Containing Radioactive Isotopes* (1953). [Superseded by NCRP Report No. 21]
17	*Permissible Dose from External Sources of Ionizing Radiation* (1954) including *Maximum Permissible Exposure to Man, Addendum to*

National Bureau of Standards Handbook 59 (1958). [Superseded by NCRP Report No. 39]

18 *X-Ray Protection* (1955). [Superseded by NCRP Report No. 26]

19 *Regulation of Radiation Exposure by Legislative Means* (1955). [Out of print]

20 *Protection Against Neutron Radiation Up to 30 Million Electron Volts* (1957). [Superseded by NCRP Report No. 38]

21 *Safe Handling of Bodies Containing Radioactive Isotopes* (1958). [Superseded by NCRP Report No. 37]

24 *Protection Against Radiations from Sealed Gamma Sources* (1960). [Superseded by NCRP Reports Nos. 33, 34, and 40]

26 *Medical X-Ray Protection Up to Three Million Volts* (1961). [Superseded by NCRP Reports Nos. 33, 34, 35, and 36]

28 *A Manual of Radioactivity Procedures* (1961). [Superseded by NCRP Report No. 58]

29 *Exposure to Radiation in an Emergency* (1962). [Superseded by NCRP Report No. 42]

31 *Shielding for High Energy Electron Accelerator Installations* (1964). [Superseded by NCRP Report No. 51]

34 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Structural Design and Evaluation* (1970). [Superseded by NCRP Report No. 49]

Statements

The following statements of the NCRP were published outside of the NCRP Report series:

"Blood Counts, Statement of the National Committee on Radiation Protection," Radiology **63,** 428 (1954)

"Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol. Radium Ther. and Nucl. Med. **84,** 152 (1960) and Radiology **75,** 122 (1960)

X-Ray Protection Standards for Home Television Receivers, Interum Statement of the National Council on Radiation Protection and Measurements (National Council on Radiation and Measurements, Washington, 1968)

Specification of Units of Natural Uranium and Natural Thorium (National Council on Radiation Protection and Measurements, Washington, 1973)

Copies of the statements published in journals may be consulted in libraries. A limited number of copies of the last two statements listed above are available for distribution by NCRP Publications.

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